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SAMPLED DATA ADAPTIVE DIGITAL COMPUTER  
CONTROL OF SURFACE SHIP MANEUVERS

John Joseph Uhrin

# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



# THESIS

SAMPLED DATA ADAPTIVE DIGITAL COMPUTER  
CONTROL OF SURFACE SHIP MANEUVERS

by

John Joseph Uhrin III

June 1976

Thesis Advisor:

George J. Thaler

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DSL simulation for a number of possible RAS scenarios. The control systems are also tested in a sea state to insure proper operation in the presence of external perturbations.

19.

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Sampled Data Adaptive Digital Computer Control  
of  
Surface Ship Maneuvers

by

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Submitted in partial fulfillment of the  
requirements for the degree of

ELECTRICAL ENGINEER

from the

NAVAL POSTGRADUATE SCHOOL  
June 1976

## ABSTRACT

The replenishment at sea (RAS) maneuver is studied in detail for heading and speed control. Design of purposefully nonlinear control laws is accomplished for the Mariner hull using the linearized equations of motion in three degrees of freedom. Extensive use of low order modeling and optimal control theory was made. Procedure steps are presented in detail to facilitate redesign for other ship types. The results are verified using DSL simulation for a number of possible RAS scenarios. The control systems are also tested in a sea state to insure proper operation in the presence of external perturbations.

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## TABLE OF TERMS AND ABBREVIATIONS

ADX - DX referenced to control ship's head  
ADY - DY referenced to control ship's head  
Alongside - position at which longitudinal position ADX is  
0.0  
Approach Phase - phase in RAS scenario at which the control  
ship comes alongside the reference ship  
Approach Speed - speed at which the control ship will  
commence approach to come alongside the  
reference ship  
AT - real time as referenced to the full size Mariner hull  
Control Ship - ship making the RAS approach  
Desired Distance - lateral distance at which RAS desired  
DSL - Digital Simulation Language (IBM developed)  
DX - center of ship's geographic separation along X axis  
DY - center of ship's geographic separation along Y axis  
Geographic Coordinates - earth's coordinate system  
JCL - Job Control Language for IBM 360/67 computer  
Kt., kts. - knot, knots - 1 nautical mile/hour or 2000  
yards/hour  
L, Ship length - length of one mariner hull used in this  
thesis (527.8 feet)  
Lateral Distance - equal to ADY  
Longitudinal Distance/Position - equal to ADX  
LUC - nondimensionalizing scaling factor  
Port Side To - approach (control) ship replenishes with its  
port side toward supply (reference) ship  
RAS - Replenishment At Sea  
Receiving Ship - control ship or ship B  
Reference Ship - ship that maintains course and speed  
Reference Speed - speed of reference ship

TABLE OF TERMS AND ABBREVIATIONS (cont.)

Replenishment Speed - signaled intended speed at which RAS  
will be conducted

Stbd Side Tc - approach (control) ship replenishes with its  
stbd side toward supply (reference) ship

Supply Ship - reference ship or ship B

T - nondimensionalized time used in DSL runs

Turn Phase - phase in RAS scenario at which the ships are in  
their desired positions and the  
reference ship is turned

Yaw - ship's heading in relation to true north

Y Coordinate - geographic reference system E is +, W is -

X Coordinate - geographic reference system N is +, S is -

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## I. INTRODUCTION

The advent of the digital computer as standard equipment on board virtually all modern Naval ships has opened the field of Digital Computer Control in almost all aspects of ship life. The computer has been a viable asset in fire control systems for years and has been used extensively for aids to ship maneuvering control in the form of NTDS (Naval Tactical Data System) readouts. The declining costs of general and special purpose computers has made their inception as a manpower replacement or augmentation a reality. Their high speed and accuracy can make them perform functions with much greater safety than previously attainable with time proven (and sometimes time weary) "seaman's eye."

This then is the basis for this thesis; a study of the types of maneuvers that can be handled more accurately and safely than presently being accomplished.

One area of study is the total Replenishment At Sea (RAS) problem including both course and speed control for the approach and alongside phases. This situation has always been one of extreme danger due to the collision potentials involved. However, other dangers are involved in the on deck evolutions when the ships are not kept at a fairly constant distance. Sudden violent maneuvers may cause the stress on the lines between ships to increase enough to cause the lines to part. The reality of this danger is readily apparent to anyone who has ever seen a Manila line or steel cable part or a kingpost shackle break or a kingpost suddenly bend under these extreme stresses. A system which will minimize these potential dangers is well

worth investigation.

Of course with a digital computer, the algorithm for RAS can be modified or replaced to enable its use as a maneuvering control device for other situations such as formation steaming or single ship navigation transit control.

## II. MODELING

### A. MARINER DYNAMICS

In the conception of this thesis, realistic models of modern destroyer hull configurations were sought. This search proved fruitless. The hydrodynamic coefficients for present day destroyers are not currently available. However, some naval and civilian research is presently being conducted to obtain these coefficients.

A complete set of these coefficients is necessary for any maneuvering control system design. A hull configuration which has been under continual study with well defined and verified hydrodynamic coefficients was chosen<sup>[1]</sup>. This hull is commonly referred to as the "Mariner" hull.

The development of the equations of motion in six and three degrees of freedom have been well documented<sup>[2]</sup>. The model used for this thesis is the equations of motion in three degrees of freedom linearized with second order and higher terms eliminated. These equations are characterized by dependency on small perturbations about a specific operating point. The maneuvers experienced in the following chapters do not entirely meet this criterion. The inadequacy and shortcomings of this model are of little consequence because relevant hydrodynamic coefficients are not available, and the methods presented can be applied to any ship type.

The development of the model is readily available to the interested reader<sup>[3]</sup>; only a summary of the equations

and their corresponding hydrodynamic coefficients are presented here.

The equations of motion used are as follows:

$$(\dot{X}_u - m) \ddot{U} + X_u (U - u_0) + X_d \dot{d} = 0$$

$$(\dot{Y}_v - m) \ddot{V} + Y_v V + (Y_r - m) R + Y_r \dot{R} + Y_d \dot{d} = 0$$

$$(\dot{N}_z - I) \ddot{\dot{F}} + N_z R + N_v \ddot{V} + N_v \dot{V} + N_d \dot{d} = 0$$

The direction and sense of the terms in the above equations are shown in figure II-1. Letting:

$$a_{11} = m - Y_v$$

$$b_{11} = -Y_v$$

$$c_{11} = 0$$

$$a_{21} = -Y_r$$

$$b_{21} = m - Y_r$$

$$c_{21} = 0$$

$$a_{12} = -N_v$$

$$b_{12} = -N_v$$

$$c_{12} = 0$$

$$a_{22} = I - N_z$$

$$b_{22} = -N_r$$

$$c_{22} = 0$$

$$a_{33} = m - X_u$$

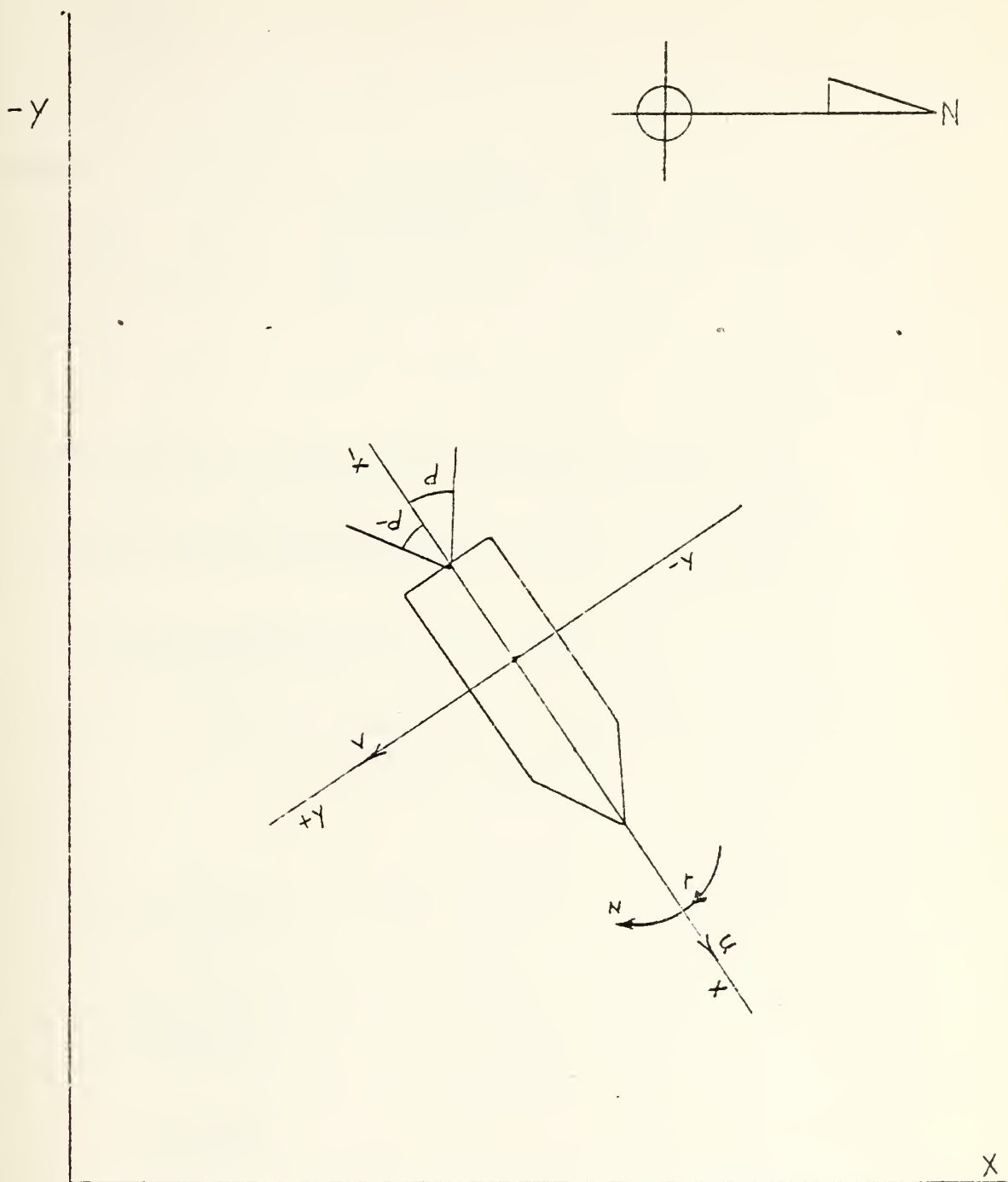


Figure II-1  
Direction and Sense of Hydrodynamic Terms

$$b_{33} = -X_u$$

$$c_{33} = 0$$

Setting

$$V = \dot{A}$$

$$\Psi = B$$

$$U = \dot{C}$$

The equations of motion can be written as:

$$a_{11} \ddot{A} + b_{11} \dot{A} + c_{11} A + a_{21} \ddot{B} + b_{21} \dot{B} + c_{21} B = IF1$$

$$a_{12} \ddot{A} + b_{12} \dot{A} + c_{12} A + a_{22} \ddot{B} + b_{22} \dot{B} + c_{22} B = IF2$$

$$a_{33} \ddot{C} + b_{33} \dot{C} + c_{33} C = IF3$$

or:

$$a_{11} \ddot{A} + a_{21} \ddot{B} = I1$$

$$a_{12} \ddot{A} + a_{22} \ddot{B} = I2$$

$$a_{33} \ddot{C} = I3$$

where:

$$IF1 = -Y_d \cdot d$$

$$IF2 = N_d \cdot d$$

$$IF3 = - \int x_u dt$$

and:

$$I1 = -t_{11} \dot{A} - c_{11} A - b_{21} \dot{B} - c_{21} B + IF1$$

$$I2 = -t_{12} \dot{A} - c_{12} A - b_{22} \dot{B} - c_{22} B + IF2$$

$$I3 = -t_{33} \dot{C} - c_{33} C + IF3$$

By solving this system of equations, the following relationships are established:

$$A = (a_{22} a_{33} I1 - a_{33} a_{21} I2) / \Delta$$

$$B = (a_{11} a_{33} I2 - a_{33} a_{12} I1) / \Delta$$

$$C = I3 / a_{33}$$

where:

$$\Delta = a_{33} (a_{11} a_{22} - a_{12} a_{21})$$

which yields the solution:

$$V = \dot{A} = v_0 + \int_{t_0}^t A dt$$

$$\psi = B = \psi_0 + \int_{t_0}^t \dot{B} dt = \psi_0 + \int_{t_0}^t [\dot{B}(0) + \int_{t_0}^t B dt] dt$$

$$U = \dot{C} = u_0 + \int_{t_0}^t C dt$$

The space coordinate system is defined as follows:

$$\dot{Y} = U \cdot \sin \psi + V \cdot \cos \psi$$

$$\dot{X} = U \cdot \cos \psi - V \cdot \sin \psi$$

where:

$$X = X_0 + \int_{t_0}^t \dot{X} \, dt$$

$$Y = Y_0 + \int_{t_0}^t \dot{Y} \, dt$$

Table II-1 summarizes the symbols and nomenclature used in the foregoing abbreviated solution of motion in three degrees of freedom. The applicable characteristics of the Mariner hull are presented in table II-2 with the corresponding nondimensionalized hydrodynamic coefficients and the DSL computer program variable names delineated in table II-3.

Computer Program #1 is the basic DSL program that was developed from these equations of motion. This program uses two ships to illustrate the turning characteristics of the Mariner hull for various rudder commands. Figure II-2 shows the difference between a step model and a ramp model rudder in a geographic plot. Figure II-3 shows the corresponding difference in yaw.

TABLE II-1  
SYMBOLS AND NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>
$X_{\dot{u}}$	derivative of longitudinal force with respect to longitudinal acceleration $\dot{u}$
$U_u$	derivative of longitudinal force with respect to longitudinal velocity $U$
$Y_{\dot{v}}$	derivative of lateral force with respect to transverse acceleration $\dot{v}$
$Y_v$	derivative of lateral force with respect to transverse velocity $v$
$Y_{\dot{r}}$	derivative of lateral force with respect to angular acceleration $\dot{r}$
$Y_r$	derivative of lateral force with respect to angular velocity $r$
$Y_d$	derivative of lateral force with respect to rudder angle $\delta$
$N_{\dot{v}}$	derivative of yaw moment with respect to transverse acceleration $\dot{v}$
$N_v$	derivative of yaw moment with respect to transverse velocity $v$

TABLE II-1 (cont.)  
SYMBOLS AND NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>
$N_{\dot{r}}$	derivative of yaw moment with respect to angular acceleration $\dot{R}$
$N_r$	derivative of yaw moment with respect to angular velocity $R$
$N_d$	derivative of yaw moment with respect to rudder angle $d$
$\dot{R}$	yaw angle acceleration
$R$	yaw angle velocity
$u_0$	initial velocity of origin of body axes relative to fluid
$\dot{v}$	transverse acceleration of ship axes relative to fluid
$v$	transverse velocity of origin of ship axes relative to fluid
$X$	hydrodynamic longitudinal force
$Y$	hydrodynamic lateral force
$\dot{u}$	longitudinal acceleration of ship axes relative to fluid

TABLE II-1 (cont.)  
SYMBOLS AND NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>
$U$	longitudinal velocity of ship axes relative to fluid
$\psi$	yaw angle
$A_t$	actual time
$T$	nondimensionalized time
$x_g$	longitudinal distance that the ship center of gravity is forward of the ships axes
$u_1$	longitudinal velocity of ship axes relative to fluid (operating point)

TABLE II-2  
CHARACTERISTICS OF MARINER-TYPE STUDY SHIP

Length, ft.	527.8
Beam, ft	76.0
Draft, ft	29.75
Displacement, tons	16,800.
Block coefficient, $C_b$	0.6

TABLE II-3

## NCDIMENSIONAL HYDRODYNAMIC COEFFICIENTS

<u>Coefficient</u>	<u>Computer Program</u> <u>Variable Name</u>	<u>Nondimensional</u> <u>Value</u>
$(X_{-m})_u$	MXUD	-0.0085
$X_u$	XU	-0.0012
$Y_v$	YV	-0.01243
$(Y_{-m})_v$	MYVD	-0.015
$(Y_{-mu})_{r1}$	MYR	-0.0051
$(Y_{-ux})_{rg}$	YRD	-0.00027
$Y_d$	YDEL R	+0.0027
$N_v$	NV	-0.00351
$N_v$	NVD	-0.000197
$(N_{-mxu})_{rg1}$	NR	-0.00227
$(N_{-I})_{rz}$	IZNRD	-0.00068
$N_d$	NDEL R	-0.00126
$X_n$	---	-0.0000462
$Y_n$	---	-0.0000052
$N_n$	---	+0.0000026
$X_d$	XDEL R	0.0

NOTE:  $x_g = 0.0$

TABLE II-3 (cont.)

NONDIMENSIONAL HYDRODYNAMIC COEFFICIENTS

Values based on the following operating point:

$$u_1 = 1.0 \text{ (15 Kts)}$$

$$\dot{\psi} = 0.0$$

$$\dot{v} = 0.0$$

Figure II-2  
Rudder Step and Ramp Model Geographic  
Comparison

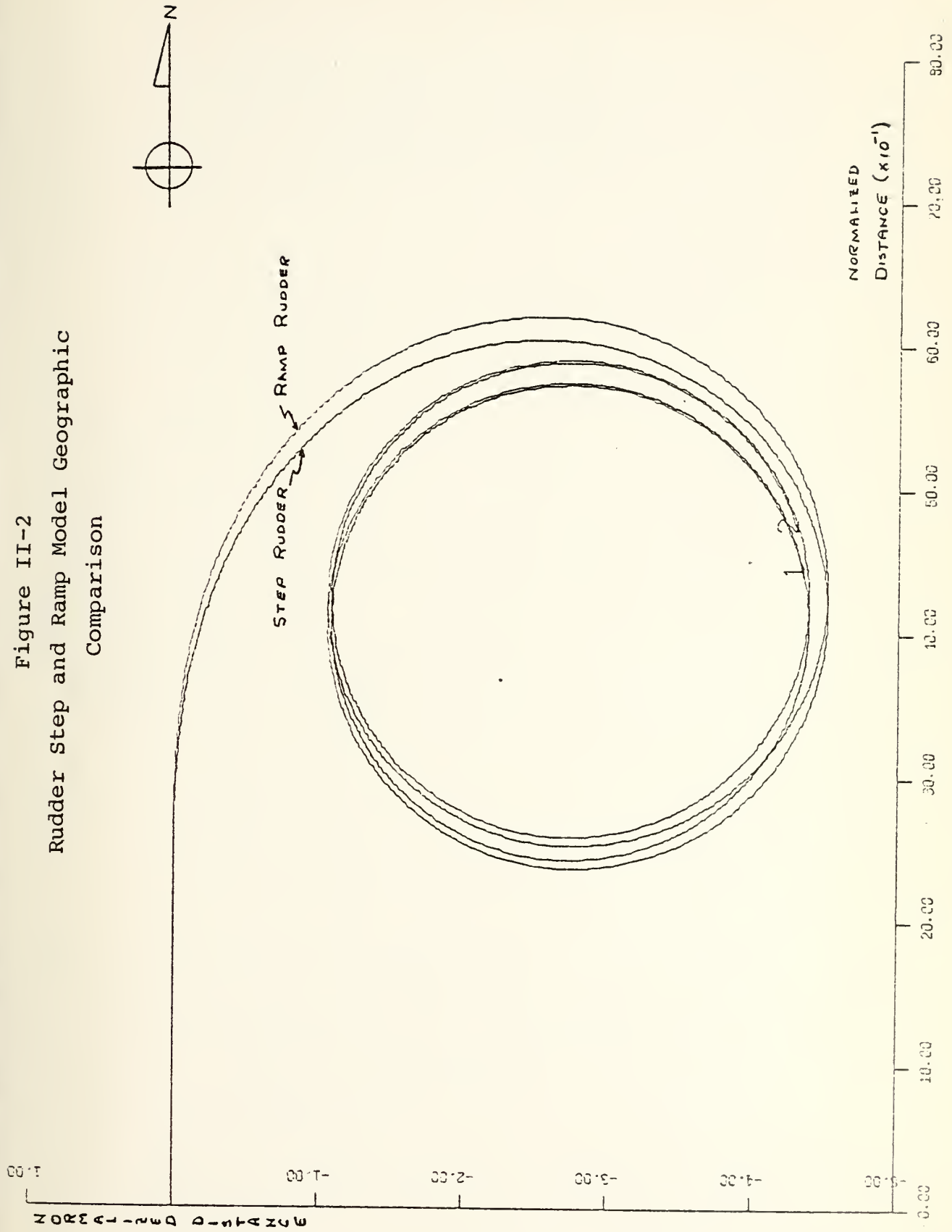
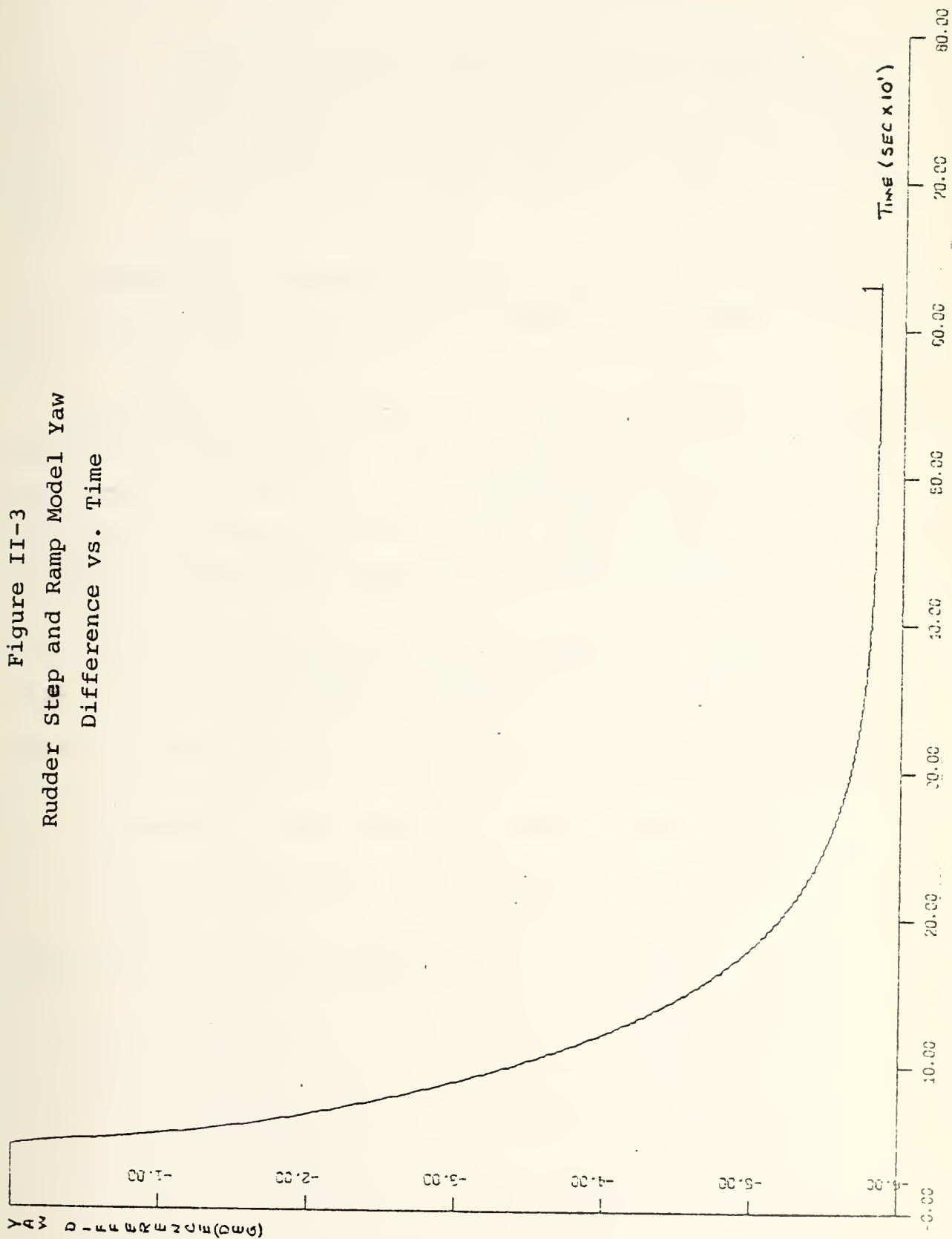


Figure II-3  
Rudder Step and Ramp Model Yaw  
Difference vs. Time



## E. RUDDER RESPONSE

The previous section indicates a marked difference in behavior between step and ramp rudder models. This prompted an investigation into realistic rudder modeling which would fulfill the requirements of limit stops and maximum rudder rate.

NSREC[\*] has modeled the rudder of the DD-931 Class Destroyer. The basics of this model are presented in the block diagram of figure II-4.

The first limiter models the rudder stops which for the Mariner are  $\pm 30$  degrees. The second limiter models the proportional band of a variable-displacement pump by limiting its maximum percent stroke. The limits for this nonlinear element have been found to be  $\pm 7$  degrees.

The transfer function ( $K_g/s$ ) accepts an input error signal of up to 7 degrees, converts it to a rudder rate, and integrates the rudder rate to obtain rudder angle. Letting:

$$\dot{d}_m = \text{Maximum rudder rate (2.0 degrees/sec)}$$

$$d_{\text{emax}} = \text{Maximum error input (7.0 degrees)}$$

The system gain can be defined as:

$$\begin{aligned} K_g &= \dot{d}_m / d_{\text{emax}} \\ &= 2.0 / 7.0 \\ &= 0.285714 \text{ /sec} \end{aligned}$$

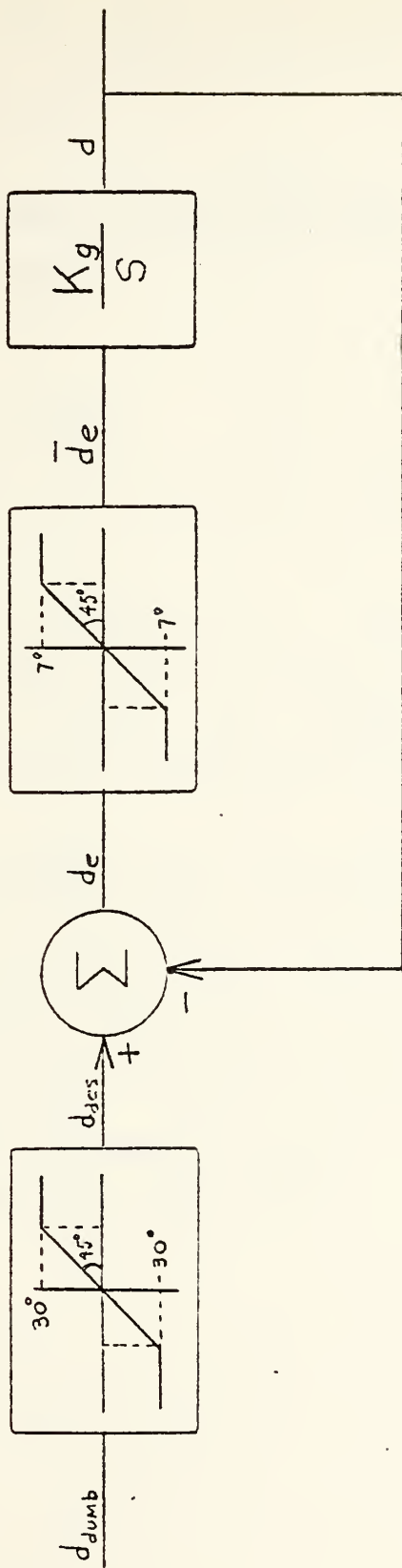


Figure II-4  
Rudder Block Diagram

To convert this model to the required nondimensionalized form, the following manipulation is required:

$$\begin{aligned}K_g' &= K_g \cdot L/u_1 \\&= 0.285714 \cdot 527.8 / (15 \cdot 1.689) \\&= 5.95224\end{aligned}$$

where:

$L$  = ship length

$u_1$  = operating point speed (15 Kts  $\cdot$  1.689 ft/sec/Kt)

Computer Program #2 is the DSL program which models this system. The curves of figure II-5 and II-6 exhibit the responses of various step rudder commands. These are tabulated and cross referenced in table II-4.

These responses show the characteristics of a realistic rudder in that the rudder is never allowed to slam into the stops. They exhibit the time delay between command and response which is a function of the rate of response (2.0 degrees/sec). A control system design with this scheme is a much more difficult problem than one with an idealized rudder (step response) because the entire rudder control system becomes quite nonlinear.

TABLE II-4

## RUDDER COMMAND AND RESPONSE

<u>Figure</u>	<u>Curve</u>	<u>Rudder</u> <u>Command(deg)</u>	<u>Initial</u> <u>Condition(deg)</u>
II-5	1	+30.0	-30.0
II-5	2	+25.0	-25.0
II-5	3	+20.0	-20.0
II-5	4	+15.0	-15.0
II-5	5	+10.0	-10.0
II-5	6	+ 5.0	- 5.0
II-6	1	+30.0	0.0
II-6	2	+25.0	0.0
II-6	3	+20.0	0.0
II-6	4	+15.0	0.0
II-6	5	+10.0	0.0
II-6	6	+ 5.0	0.0

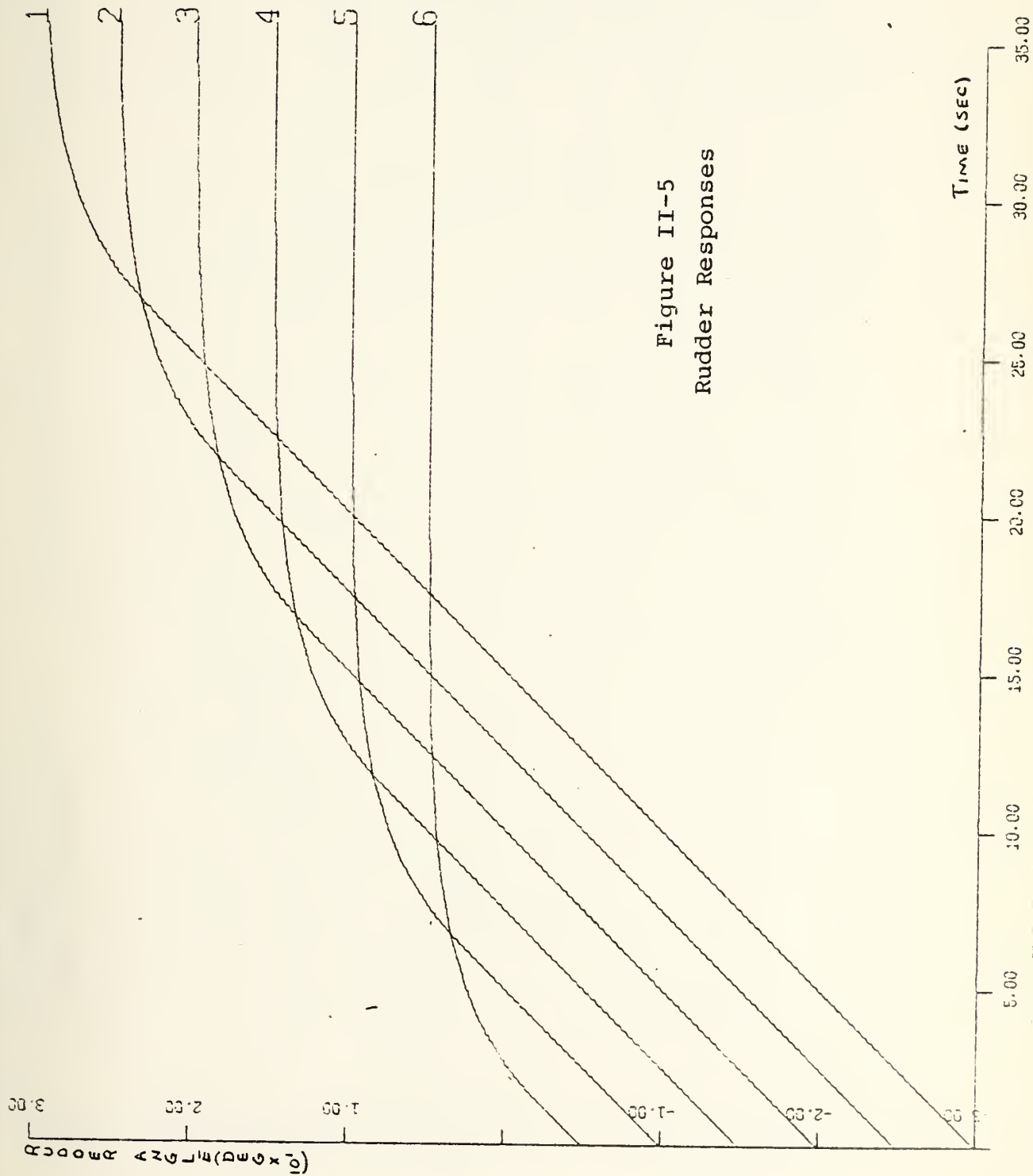
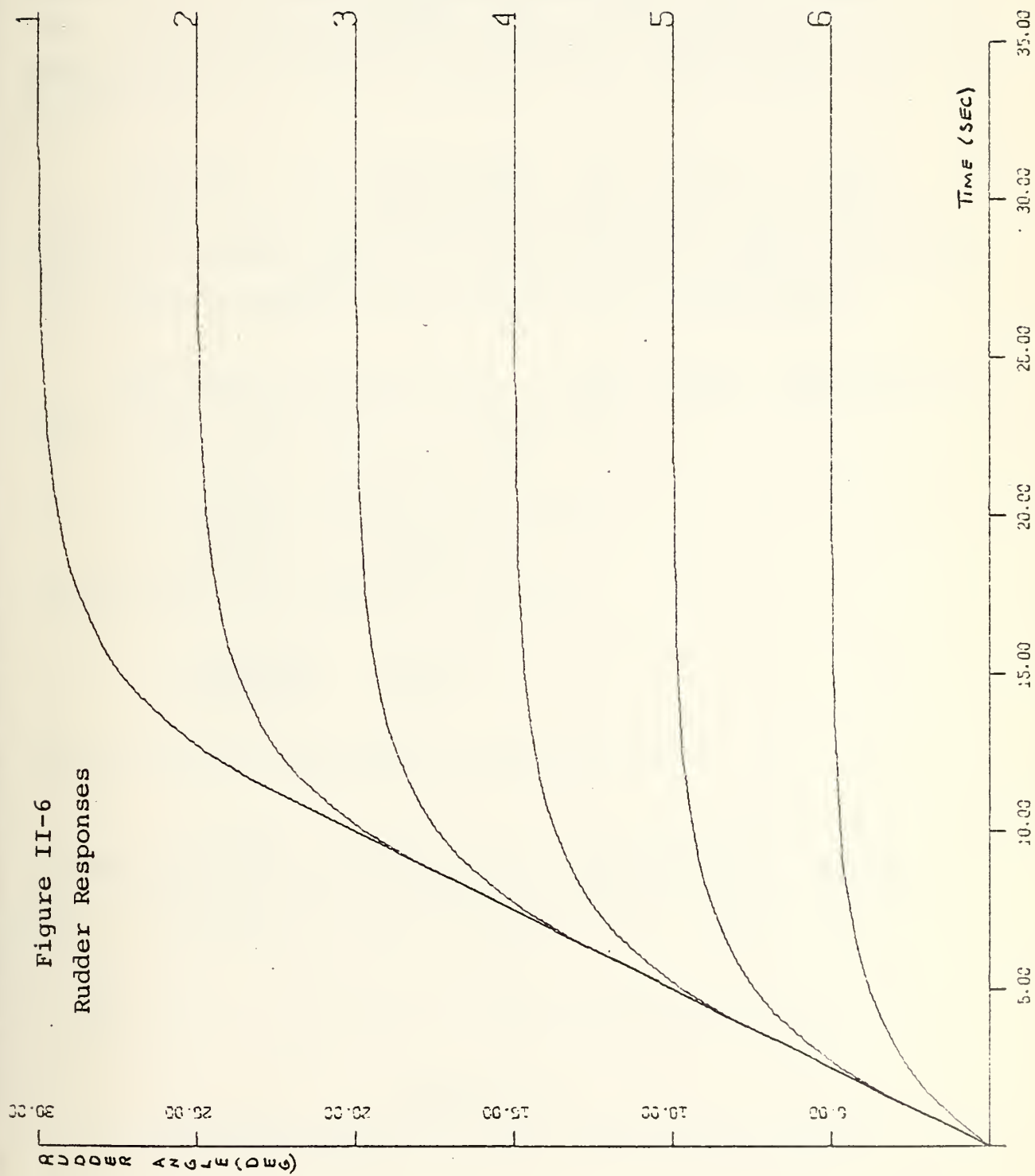


Figure II-5  
Rudder Responses

Figure II-6  
Rudder Responses



## C. ENGINE RESPONSE

Figure II-7 portrays a complex model of a gas turbine propulsion plant<sup>[5][6]</sup>. This model contains the elements required for a complete dynamic study of the system. For the purpose of this thesis, such a complicated model is not required if the overall input-output relationship can be established.

Reference 5 establishes an output speed (U) relationship for a step input of desired speed (U<sub>d</sub>) and is redrawn as figure II-8. The relationship appears to be that of a first or second order system with a time delay.

The system equations for a first order approximation with a time delay may be written as:

$$\begin{aligned} \text{SPDIN} &= K * \text{SPDDES} * e^{-Ts} \\ \text{SPDERR} &= (\text{SPDIN} - \text{SPDCUT}) * G \\ \text{SPDCUT} &= \int \text{SPDERR} dt \end{aligned}$$

Which yields the transfer function:

$$\frac{\text{SPDCUT}(s)}{\text{SPDIN}(s)} = \frac{G * K * e^{-Ts}}{s + G}$$

Which is block diagrammed in figure II-9.

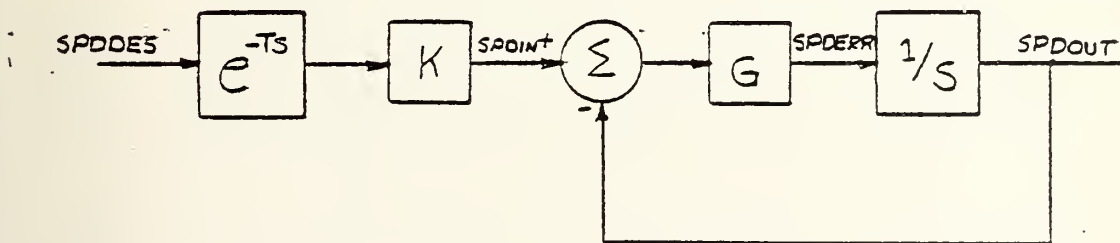
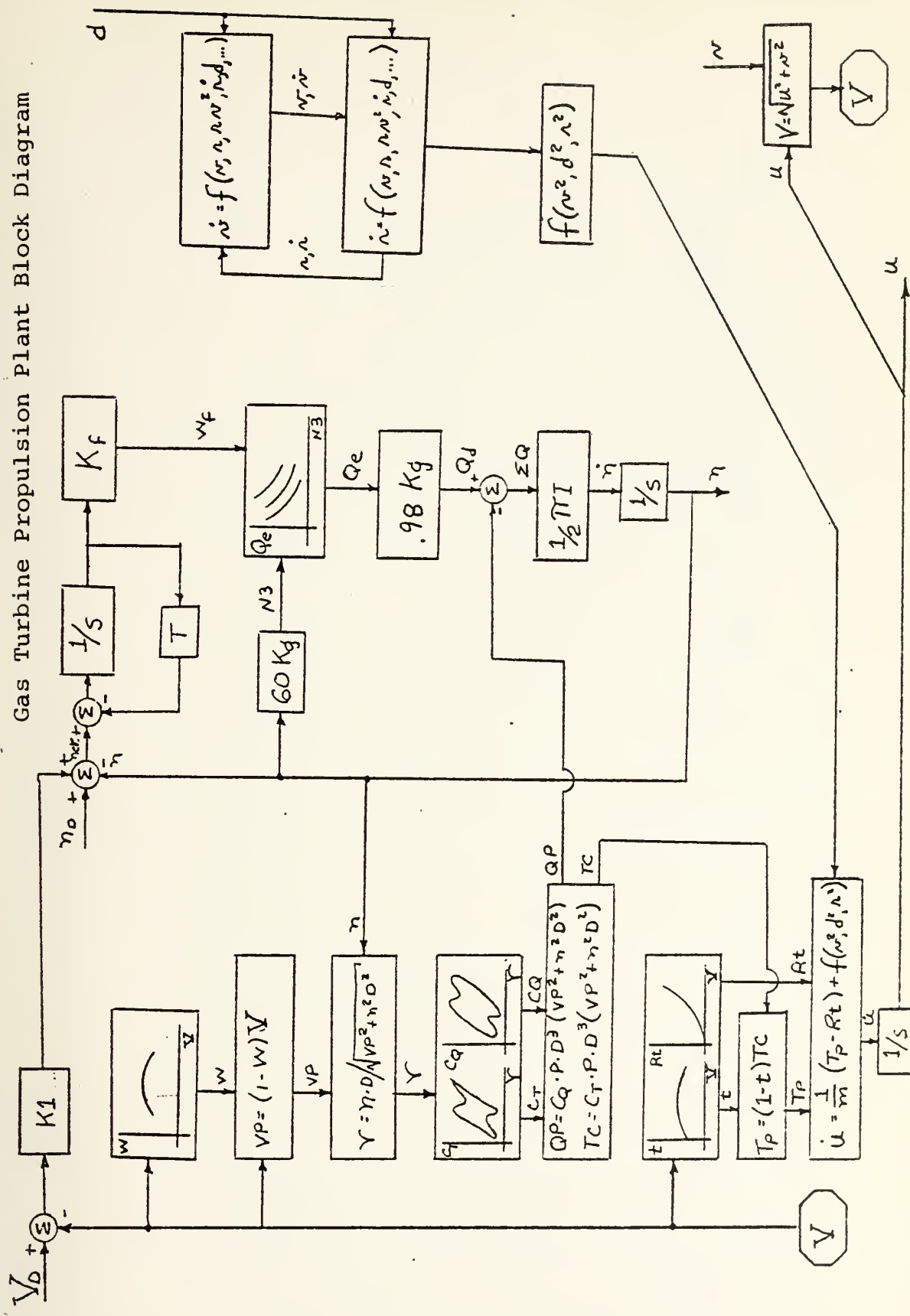


Figure II-9

Propulsion Plant Low Order Model Block Diagram

Figure II-7

Gas Turbine Propulsion Plant Block Diagram



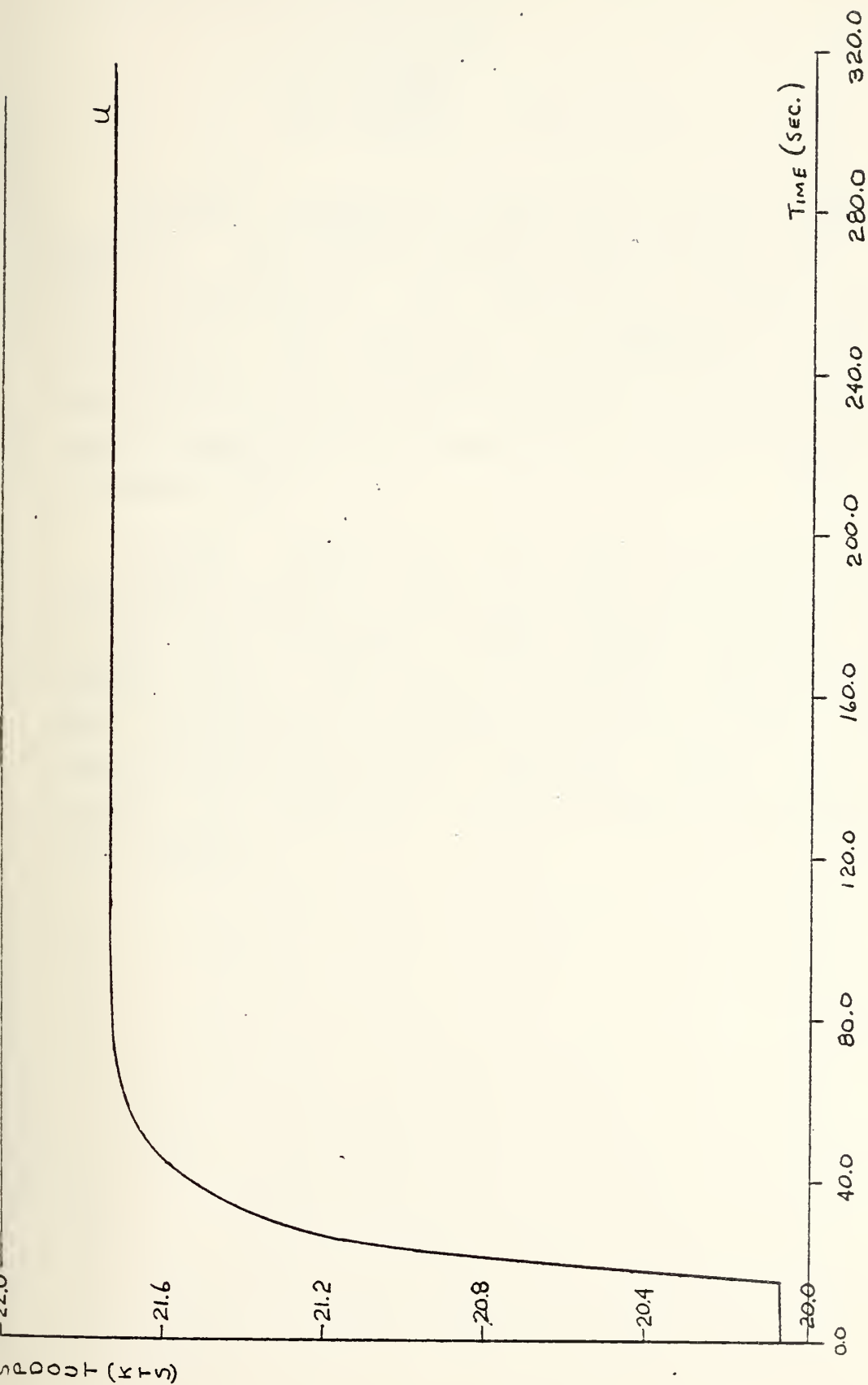


Figure II-8  
Propulsion Plant High Order Model Step Response

From figure II-8, the time delay, system gain, and time constant can be estimated as:

$$T = 4.88 \text{ sec}$$

$$K = 0.9877$$

$$G = 0.092$$

Computer Program #3 was used to obtain the step input response. The original complex system output and the low order approximation are compared in figure II-10. As indicated in this figure, the two responses are very close. Considering the linearized approximations made in the equations of motion, this response is accurate enough for system study use and is used as the model for speed control in chapter III.

Similar methods may be used to obtain simplified low-order models for other high-order propulsion systems now in use (e.g. pressure fired boiler systems, 1200 lb. systems, etc.). They may not, however, simplify to a first order approximation suitable for system study. A method of computer determination of low-order models of high-order systems is contained in ref. 7 and may be mechanized for this purpose.

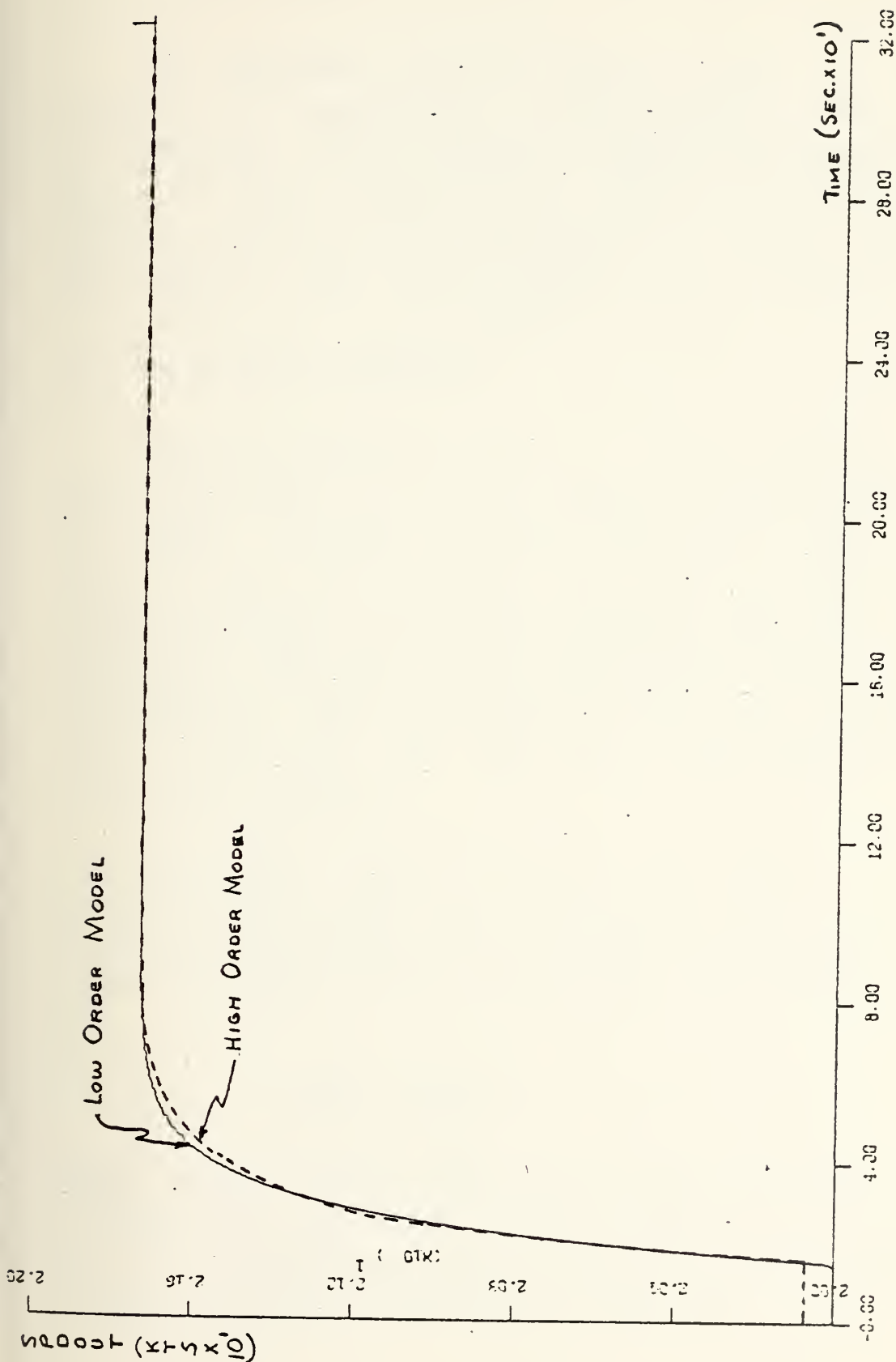


Figure II-10  
Step Response Comparison of Low and High Order Propulsion  
Plant Models

## D. EXTERNAL FORCES

The modeling of ship dynamics cannot be complete without the introduction of external forces which perturb its responses. These forces are caused by many factors and some are more relevant than others in the scope of this thesis. The two that are considered can cause substantial perturbations that must be modeled and eventually accounted for in the control system design.

### 1. Two Ships in Proximity

Whenever two ships operate in close proximity (less than 250 feet), suction and pressure forces between hulls are present. Studies have been conducted on the Mariner hull[1] which have produced data for construction of a family of curves for two ships passing on the same heading. No data has been found for the cases of two ships not on the same heading. Other restrictions on the work presented in ref. 1 are that the ships are of the same type and of similar hull ratios.

Interactive effects vary as the square of speed. However, this is only true if both ships are at the same speeds. The interaction modification factor is based on the normalized speed of 15 kts. This factor can thus be written as:

$$SPDF = CDOT1^2$$

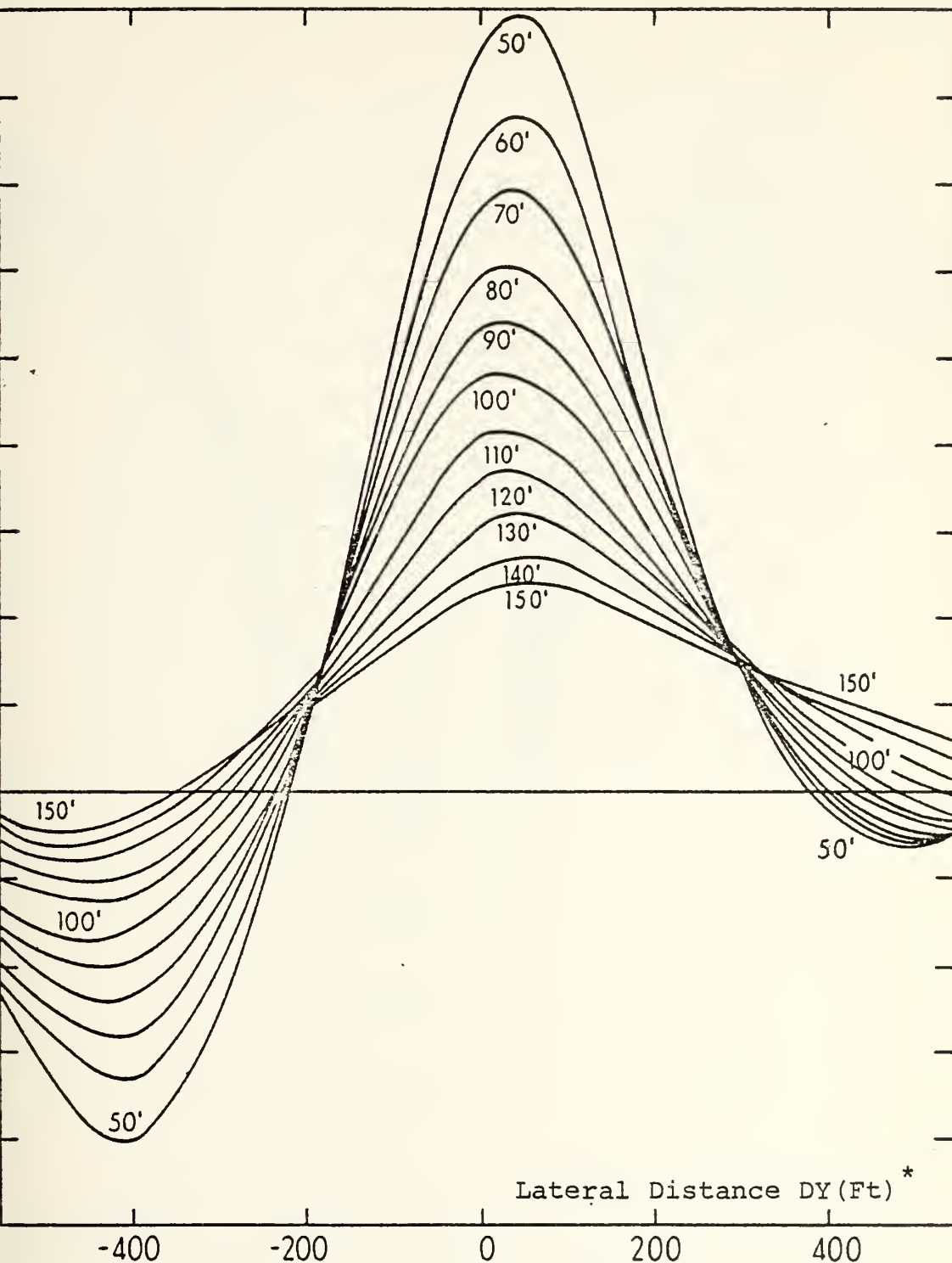
Exact effects on the interaction forces and moments in the situation where the ship's speeds differ are not available. This is inconvenient since during the approach phase, the normalized speed of the approach ship (ship B) can be as

high as 1.5. If the effect on ship B is as stated above but with its own speed causing the interaction modification, the interactive forces and moments can be 2.25 times greater than without speed considerations.

Without the ability to pin down this relationship, it was ignored in the development of the control laws presented in this thesis. Appendix C was written with the expressed intent of illustrating the effect of modifying the interactive forces and moments to the extremum case mentioned above. It must be realized that this case is not considered likely in that it is felt that the interactive forces and moments modification on ship B are more apt to be caused by the speed of ship A. If this is so, since ship A is kept at a constant 15 kts., the interactions need no modification for speed consideration in this thesis.

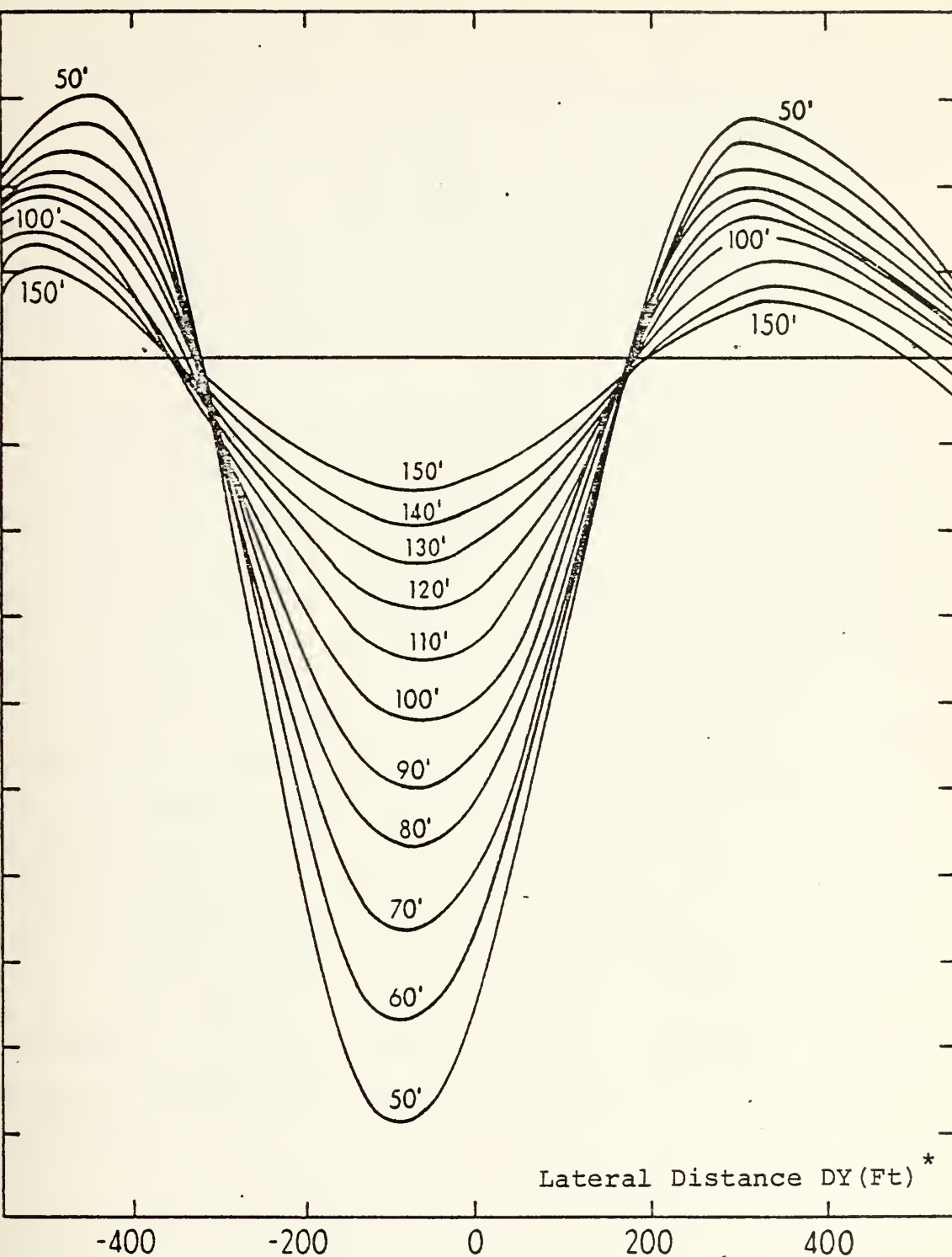
Reference 1 also gives a method of modifying the interactive forces and moments based on different ship lengths. For ease of computation and graphical presentation, the two ships were considered of equal lengths. To modify this to ships of dissimilar lengths, the resulting hydrodynamic derivatives must be modified as shown in ref. 1 (also shown in appendix C).

Since no closed form expression existed for these forces, the family of curves reproduced as figures II-11 and II-12 were quantized in subroutine SLOPES (an adaptation of the subroutine of the same name from ref. 11). (Appendix C contains a curve fitted subroutine that was compiled after the completion of the research on this thesis. It was not used for any design or simulation runs except for those presented in that same appendix.) An interpolation algorithm is used to approximate the intermediate values between quantized values and between the curves of the family.



\*Note: To convert to normalized lateral distance DY -  
Divide by the ship length L.

Figure II-11  
Family of Interactive Y force Curves



\* Note: To convert to normalized lateral distance DY -  
Divide by the ship length L.

Figure II-12  
Family of Interactive N Moment Curves

The main purpose of this subroutine is to compute the interactive forces between ships in the replenishment at sea situation and output the values for perturbation of the control ship only. Even though both ships are affected by these perturbations, a one ship control system which is effective regardless of the other ships motion is considered. Consequently, the interactive forces on the second ship are ignored.

Subroutine SLCPEs is contained in appendix A. Figure II-13 is a geographic plot of the two ships passing at 105.6 feet with their rudders amidships (0 degrees). Figure II-14 and figure II-15 show the magnitude of the lateral force (Y force) and rotational moment (N moment) of the reference ship on the ship making its approach (control ship). The reference ship is at 15 kts. and the approach ship is at 22.5 kts. The control ship starts its approach 5 ship lengths (2639.0 feet) astern and 0.4 ship lengths (211.12 feet) laterally displaced. The most graphic portrait of the effects of these forces and moments appears in the yaw changes which are presented in figure II-16. From these figures it becomes readily apparent that these perturbations cause violent motions of the ship which must be accounted for in any control system development. Throughout the development of such a control system in chapter III, these forces and moments are considered inherent in the model for RAS control.

## 2. Waves

The modeling of sea state in the form of waves and wave interactions has occupied the time of many researchers [8][9]. The exact formulation of waves will not be accomplished in this thesis. Since the main concern here will be to test the control scheme developed in chapter III, a much simplified wave generator can be used. To introduce the required experimental perturbations on the designed control system a periodic wave system with a fundamental frequency and its second harmonic is used. Some small random wave properties are introduced that ride on these two sinusoids. A simple expression of this combined wave can be written as:

$$W = WF \cdot \sin(WE) + (PI \cdot WF^2 / WL) \cdot \sin(2 \cdot WE) + WF \cdot WRV \cdot \sin(WE)$$

where:

W denotes the Wave

WF is the Wave Force

WE is the Wave Encounter radian Frequency

WL is the Wave Length

WRV is the Wave Random Variable

PI is 3.1415926

With this wave as a basis, a method of modeling this in the dynamic environment of the total ship simulation was defined. The modeling includes the introduction of this wave into the three degree of freedom equations of motion. To accomplish this a set of defining relationships were developed. First the general wave direction is input to establish the direction of the wave encounter on the ship. If the ship direction is YAWDP2 and the wave direction is WD, the expected wave direction is defined as:

$$EWD = WD - YAWDP2$$

Next the wave encounter frequency (radian frequency) can be established with knowledge of the ships normalized true speed (CDCT2), wave length (WL) and normalized wave velocity (WV). The wave encounter frequency (WEF) is then:

$$WEF = 2 \cdot \pi \cdot (CDCT2 + WV \cdot \cos(EWD)) / WL$$

The total wave encounter (WE) is nothing more than the wave encounter frequency (WEF) times time. This gives the wave encounter radian frequency required in the simple expression for the combined wave previously shown.

This does not complete the task, since the individual wave forces of each degree of freedom must be derived for this general wave expression, namely the components of WF. Again a much simplified version of the more complex real life wave forces were used. The X and Y forces are considered first. These can be modeled as cosine and sine functions of the expected wave direction (EWD) such that:

$$WFX = WF \cdot \cos(EWD)$$

$$WFY = WF \cdot \sin(EWD)$$

where WF is the total wave force of the encountered wave.

The rotational N forces are a little more difficult to establish. By considering that no rotational forces are created by a wave directly on the bow or stern, or directly off the beam, and that it is maximum when the wave is at 45 degrees off the bow or stern, a much simplified approximation is developed. Realizing that this method is very crude, the N force can be written as:

$$WFN = WF \cdot \sin(2 \cdot EWD)$$

To add more creditability to the wave model, a random

variable is added to the wave force at the waves fundamental frequency. A gaussian (normal) distribution was chosen with a zero mean and a standard deviation of one-tenth the maximum allowable force of WF. A zero mean signifies that the expected amplitude of the random wave is 0.0, while the standard deviation signifies that 68% of the random waves will have amplitudes less than one-tenth of the maximum allowable force of WF. Also, 94% will have amplitudes less than one-half the maximum allowable force of WF. This small added perturbation allows for verification of the model simulation with a stochastic force, which in turn adds creditability to the developed control systems.

What remains is to define the total wave force (WF). It is important not to fall into a common simulation pitfall which inevitably causes unneeded design changes. A sea state does not increase at an infinite rate. It therefore is incorrect to start a simulation with initial conditions set for calm sea and immediately introduce a high sea state perturbation. The initial large perturbation transient can give results that are not only unrealistic, but can cause the model and control system to produce unstable results. This is especially true in this case since the linearized (small perturbations about an operating point) equations of motion are used.

With this in mind, a ramp feed in of the wave force with a limiter at the desired maximum wave force (WFMA) was used. The slope of the ramp was established to impart minimum initial transients, yet increase the wave force to an acceptable testing level within the time frames of the simulations of chapter III. The slope is designed such that the maximum wave force is reached in 94.815 seconds actual simulation time (4.548 seconds problem time).

Computer program #4 was used to verify the wave action

model. Table II-5 on page 56 indicates the figures produced and changes in input wave length (WL) and wave direction (WD) for each run. The input parameters that were constant for all runs are tabulated below:

$$YAWDF2 = 0.0$$

$$CDCT2 = 1.5$$

$$WS = 5.0^*$$

$$WFMA = 0.1137$$

\* NOTE: WS is the unnormalized wave speed. Conversion to normalized wave velocity is:

$$WV = WS/15.0$$

Introduction of the wave forces is accomplished by multiplying the established wave forces by the rudder hydrodynamic coefficients for the individual reference directions. This effectively scales the wave forces to the ship model being used. The wave force result is coded in the ship simulation program as follows:

$$IF12 = RA1 \cdot D2 + YY2 + KA1 \cdot WY$$

$$IF22 = RE1 \cdot D2 + YN2 + KB1 \cdot WN$$

$$IF32 = RC1 \cdot D2 + NC2 + KC1 \cdot WX$$

Detailed results of the wave force effects are given in chapter III and will not be dealt with here.

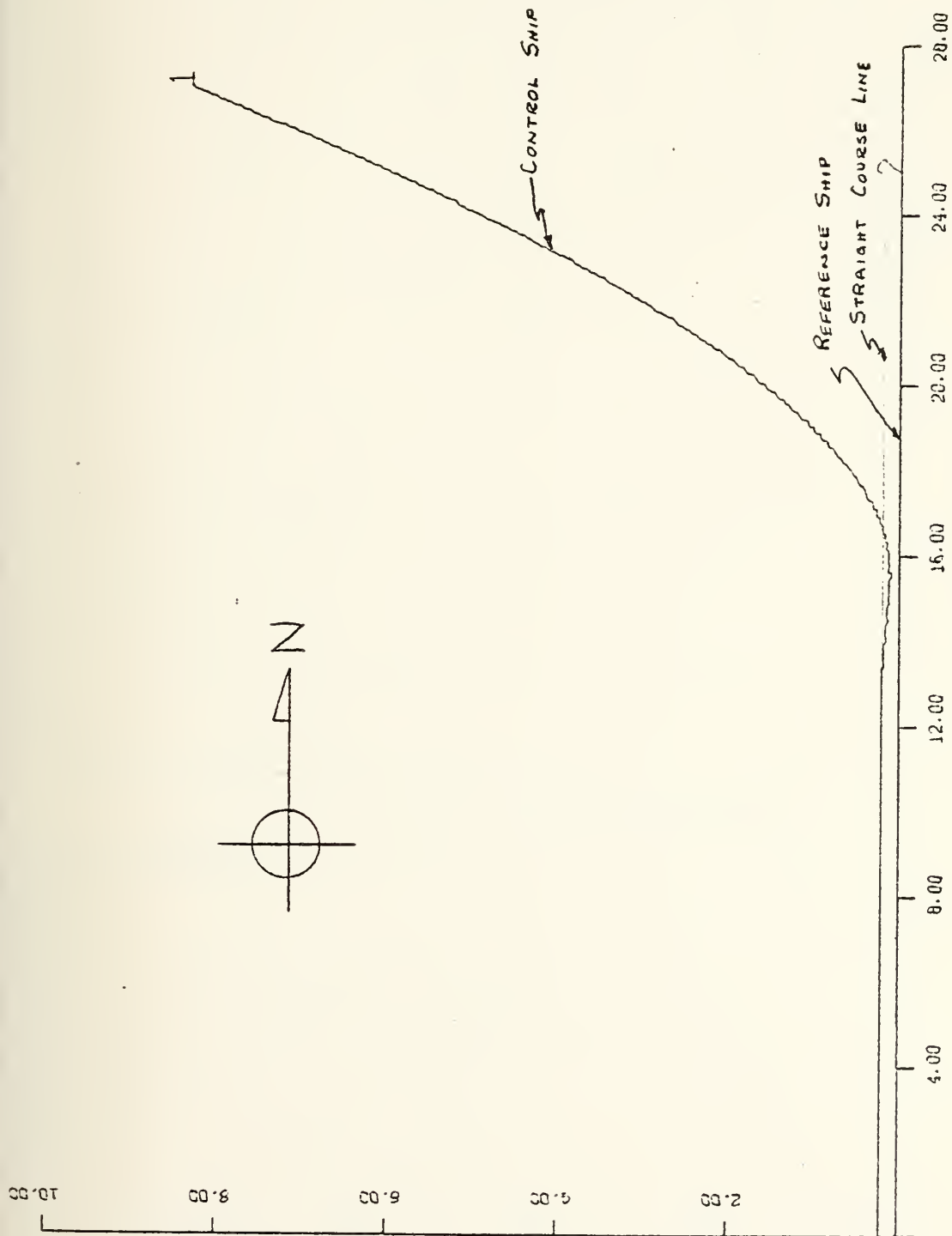


Figure II-13  
Interactive Forces Effect on the Geographic Plot



Figure II-14  
Lateral (Y) Forces

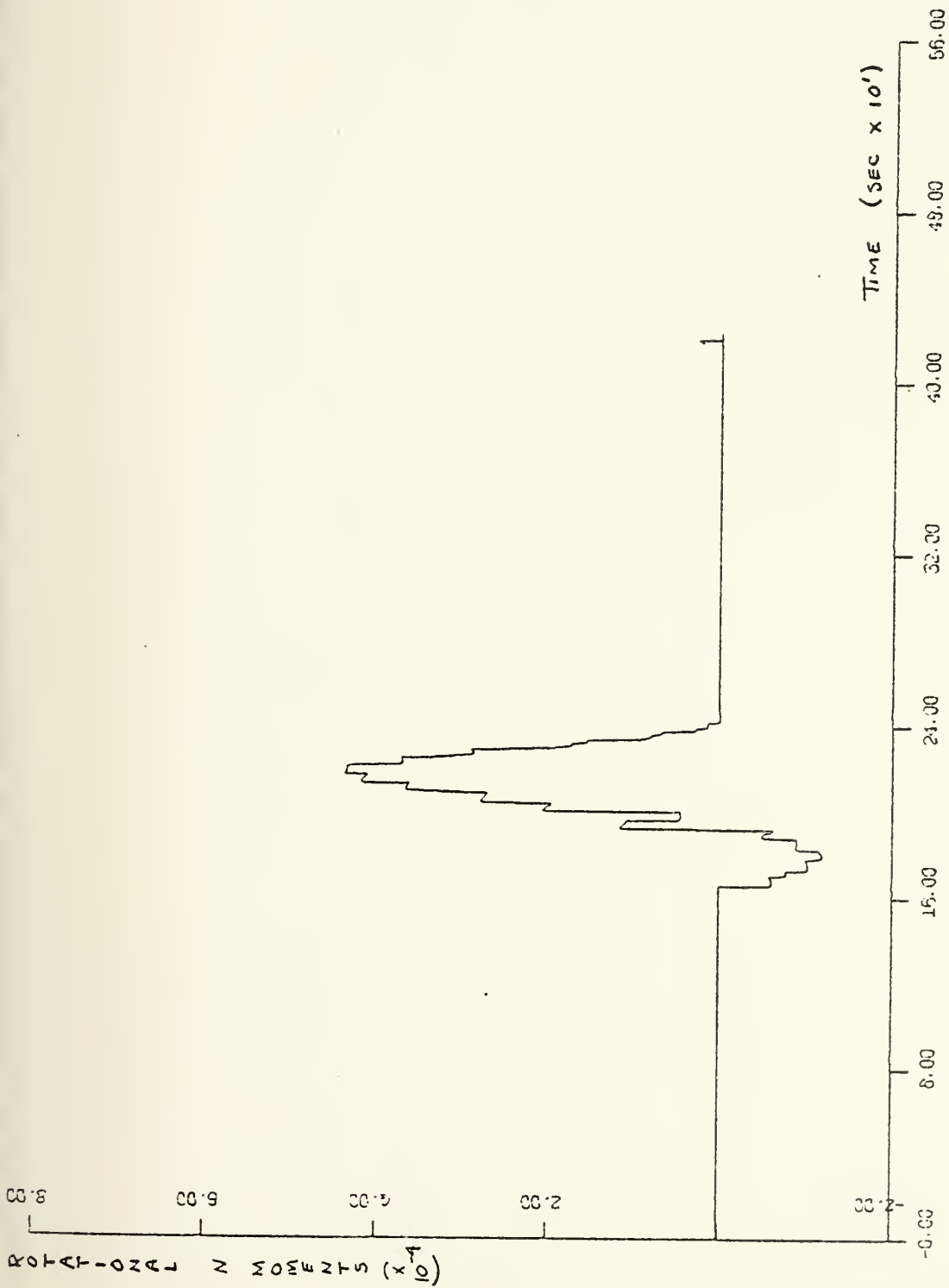


Figure II-15  
Rotational (N) Moments

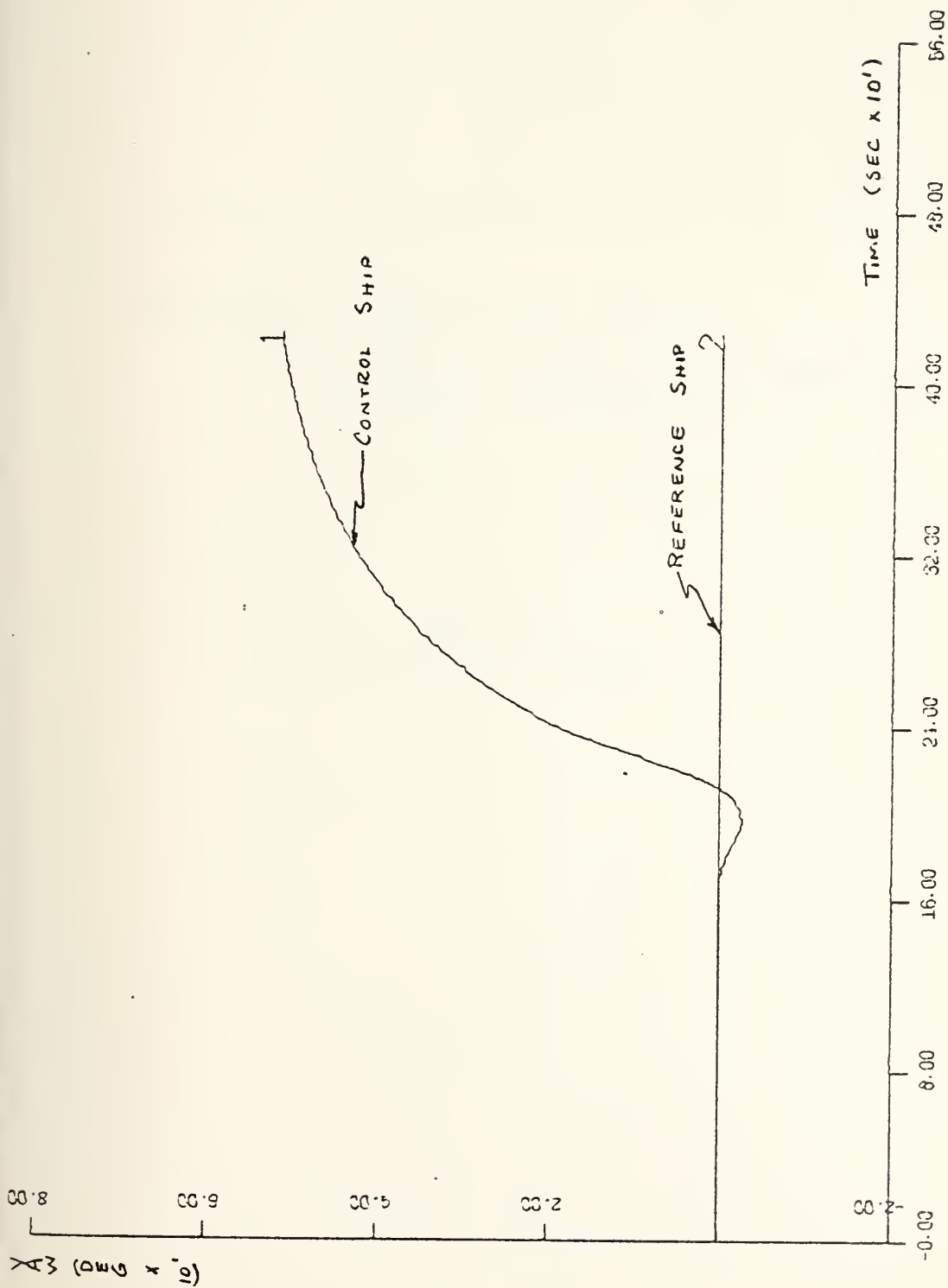


Figure II-16  
Interactive Forces Effect on Yaw of the Control Ship

Run	Figure*	Input Parameters	
		WL*	WD*
1	II-17	0.5	015
2	II-18	1.0	015
3	II-19	1.5	015
4	II-20	0.5	030
5	II-21	1.0	030
6	II-22	1.5	030

\* NOTE: WL is given in ship lengths  
WD is given in degrees  
Curve numbers of all runs corresponding to  
wave force components are:

Force	Curve
WX	1
WY	2
WN	3

Table II-5  
Wave Simulation Listing

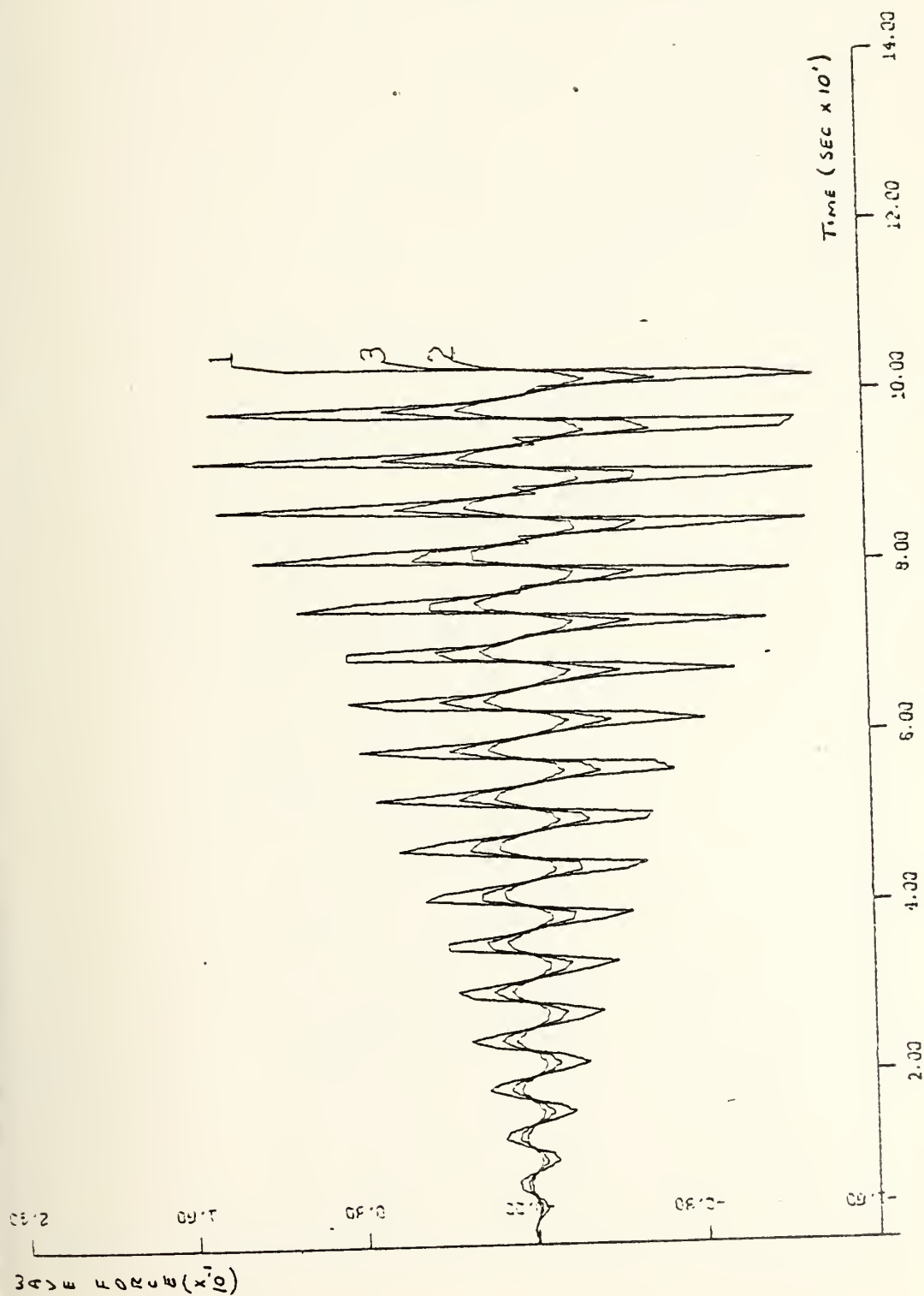


Figure II-17  
Wave Simulation Run #1

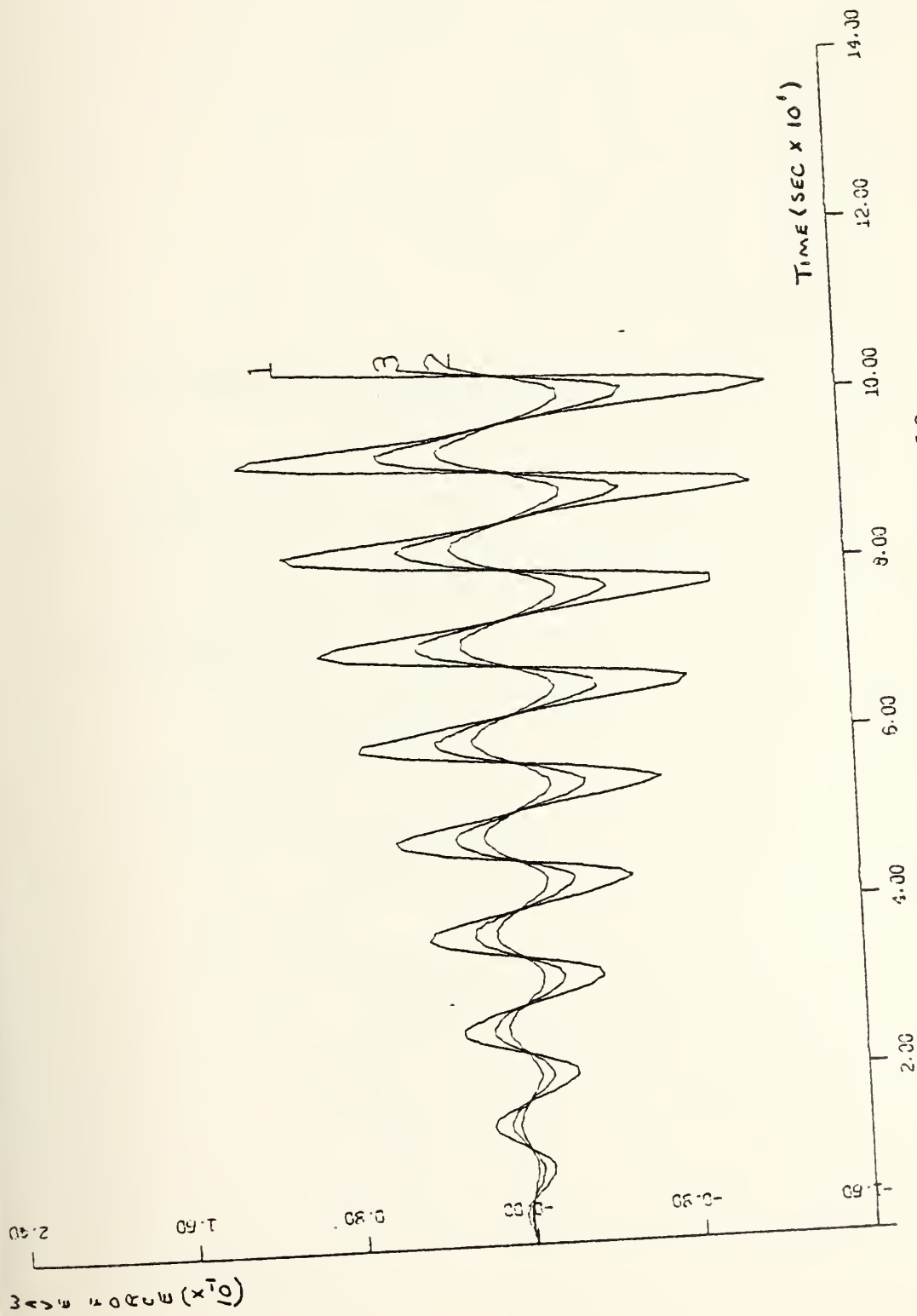


Figure II-18  
Wave Simulation Run #2

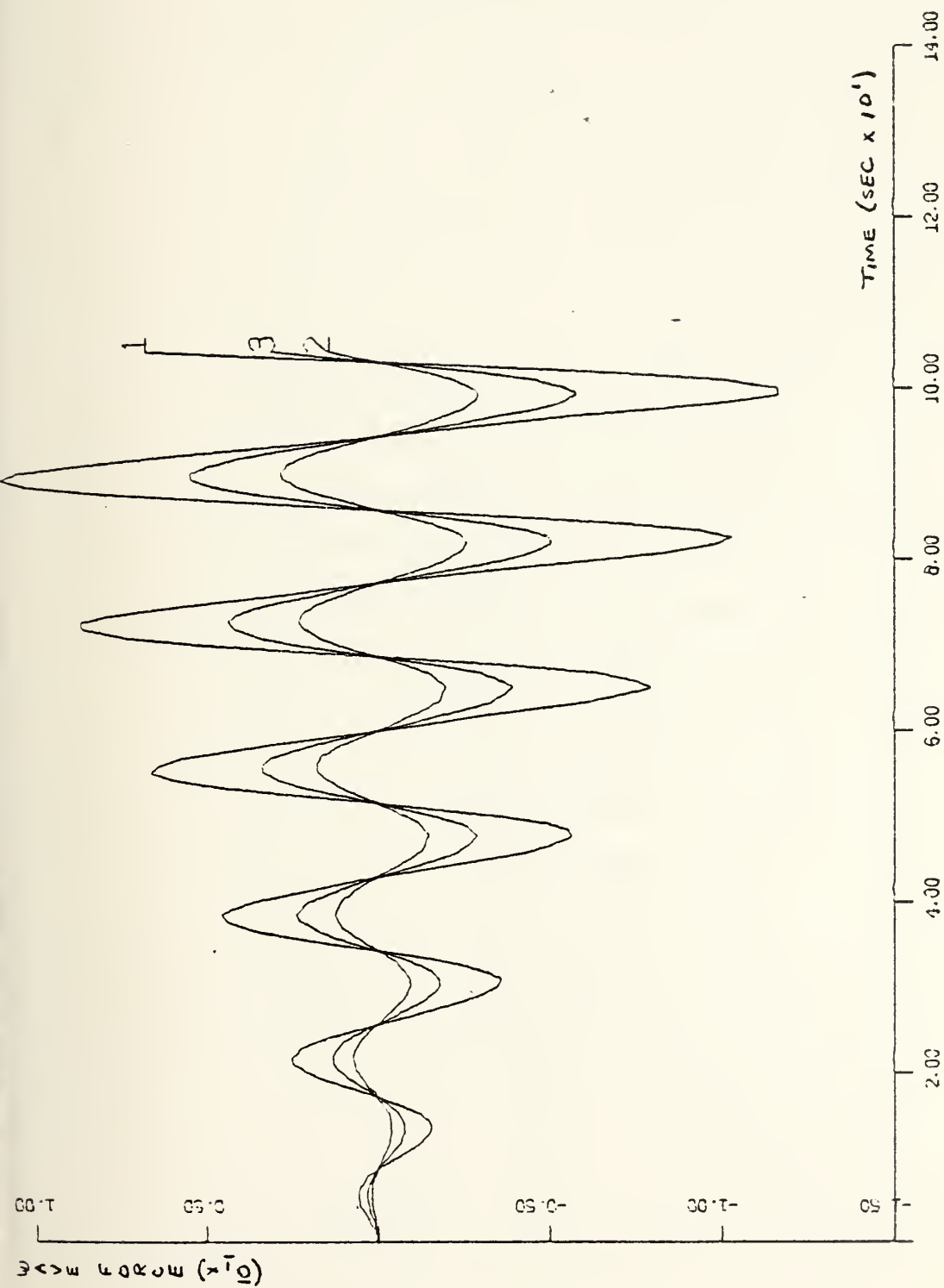


Figure II-19  
Wave Simulation Run #3

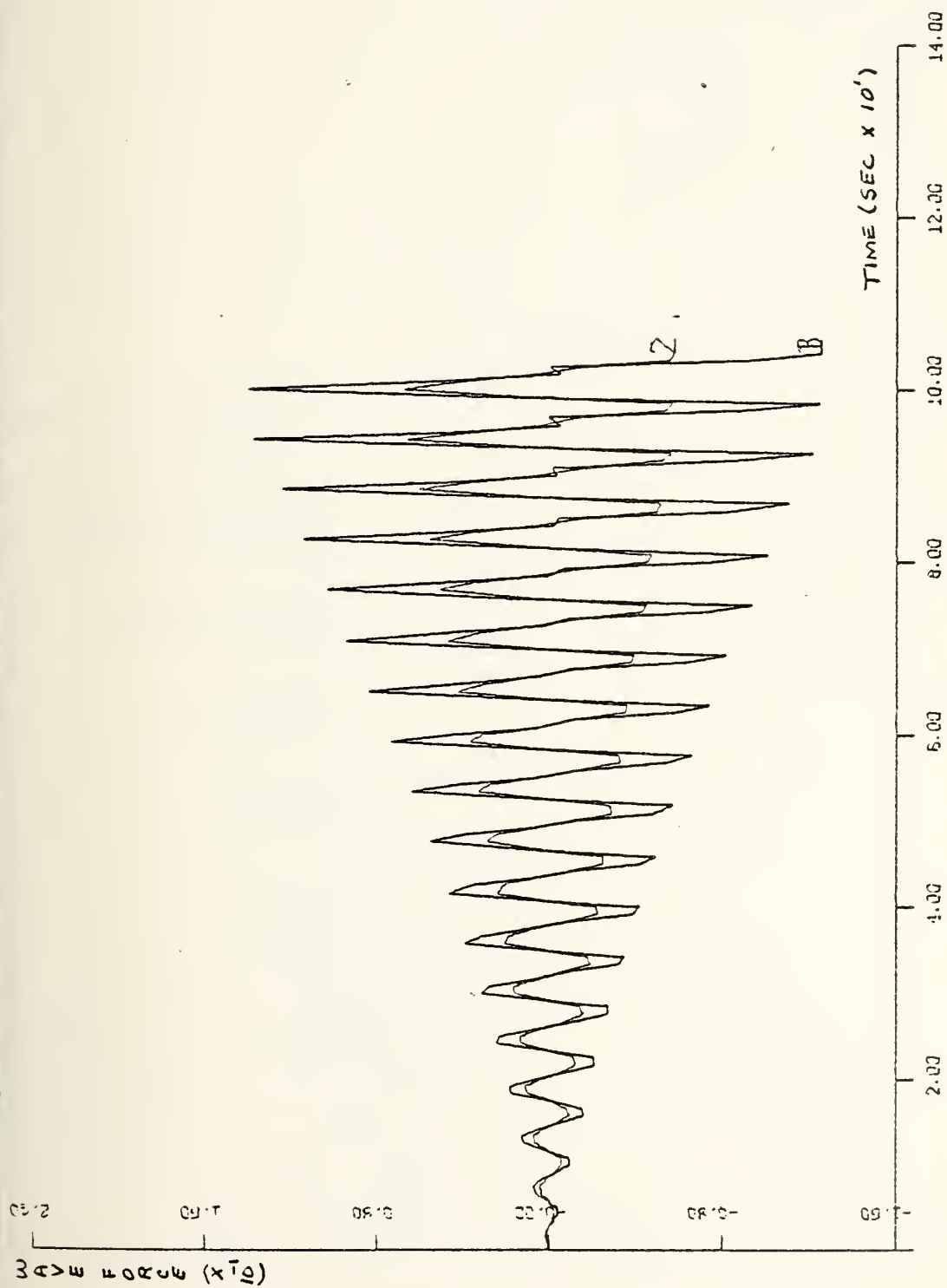


Figure II-20  
Wave Simulation Run #4

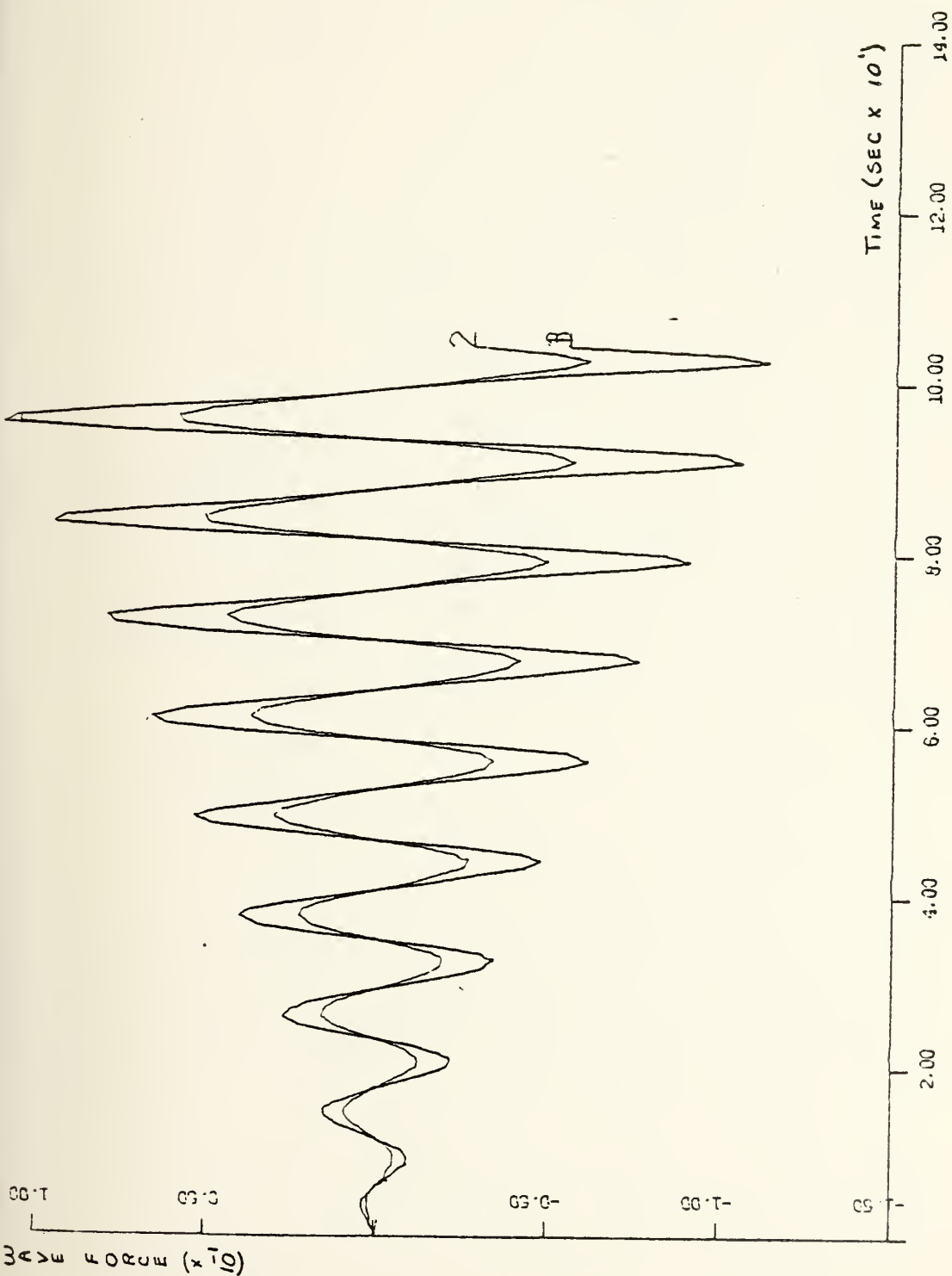


Figure II-21  
Wave Simulation Run #5



Figure II-22  
Wave Simulation Run #6

### III. REPLENISHMENT AT SEA

#### A. HEADING CONTROL

##### 1. Control Choice

Many studies involving replenishment at sea (RAS) have treated the problem as a multivariable system<sup>[10][11][12][13]</sup>. Academically, there is nothing wrong with this approach. However, as a practical system it leaves much to be desired. The key drawback in the multivariable system is the inescapable dependency on a command and control link between the replenishment ships. The unreliability of UHF communications at these close distances is a much experienced phenomenon. It is felt that any knowledgeable commanding officer would not entrust the safety of his ship to such a questionable link. An alternate method which is described here is a modern extension of the long trusted "seaman's eye" concept, where the sensors and control devices must be self contained on the ship making the approach (hereafter referred to as the receiving ship or ship B).

In all present day RAS operations, the ship on which the approach is being made (hereafter referred to as the supplying ship or ship A), must maintain the replenishment course and speed. The receiving ship accomplishes the maneuvers to maintain station relative to the supplying ship.

The parameters which are presently measured "visually" are relative position (in both the X and the Y directions),

relative head (usually in reference to ordered replenishment course), and relative motion in the X direction (for speed matching). These parameters are usually visualized by the conning officer who in turn gives corrective orders to the helmsman. The helmsman must then translate these verbal orders into rudder and speed commands through the helm and lee helm consoles. The accuracy of the execution of the conning officer's orders is extremely dependent on the ability of the helmsman and throttlesman. This system can be quite effective, and it can also be quite disastrous. This fast reacting and constantly changing environment lends itself to breakdown in communications and manifests the inability of some individuals to cope with the required critical man-machine interfaces.

To eliminate these problems, present state of the art digital computers and sensors are available for immediate implementation of a completely automatic ship control system. Such a control system may be installed on individual ships and be used for RAS without the requirement of having the matching installation on the other ship of the hockup (another drawback of the multivariable approach).

## 2. Control Method

One of the many pitfalls that may be encountered in digital simulation is the reality of the parameters that are measurable in the real world situation as opposed to those that are incidentally available in the simulation. With this fact as a keynote, Subroutine RBMEAS (Range and Bearing MEASurement) was developed. This subroutine, as listed in appendix A, defines the forward (FWD) and after (AFT) relative and true bearings, and ranges from the receiving ship to similar points on the supplying ship. Figure III-1 delineates the terms used in the subroutine. The SDFn terms

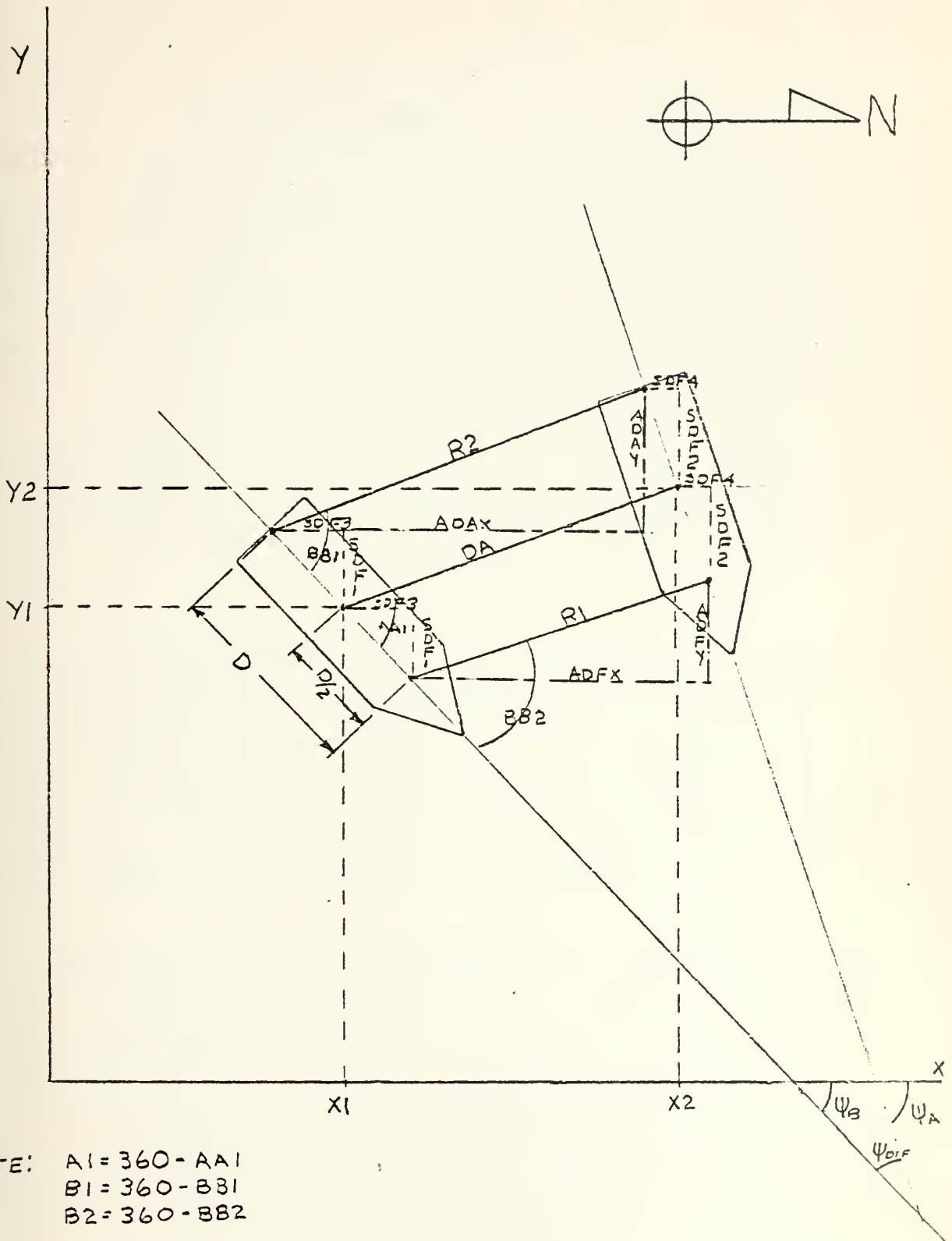


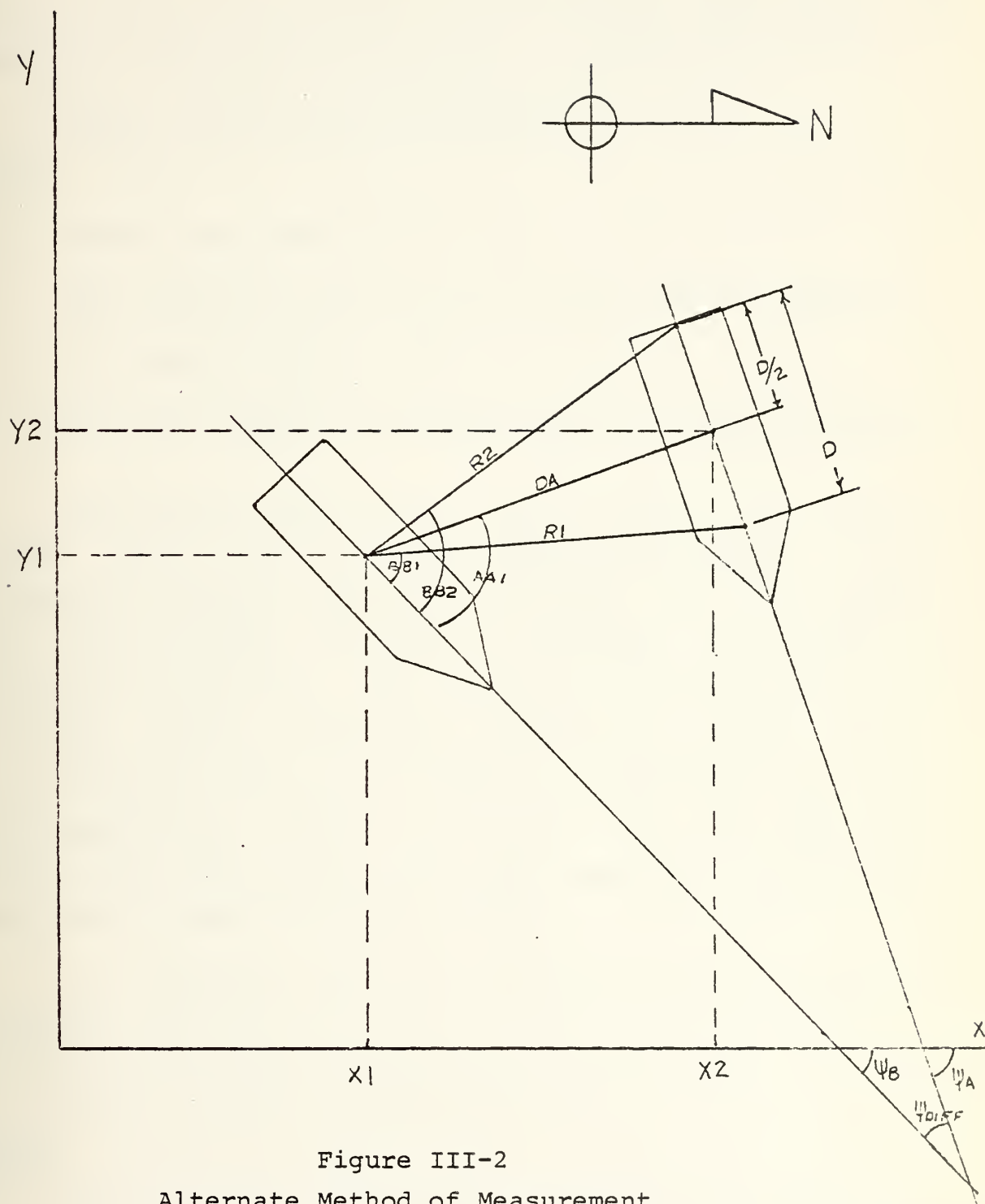
Figure III-1  
 Measurement Techniques

are used to position the bow and stern sensors and reflectors on ship B and A, respectively, in geographic coordinates as a function of ships head. The FWD distance on the X coordinate is ADFX and the Y coordinate is ADFY. Similarly, the AFT distances are ADAX and ADAY. R1 and R2 are the FWD and AFT ranges measured by a highly accurate ranging device installed on ship B. This same ranging device, if properly provided with a pinpoint reflector on the supply ship(ship A), will give accurate relative bearings FWD and AFT., B1 and B2 respectively. The distance between sensors may be varied, but as a rule should be kept as far apart as possible to allow maximum sensitivity. The distance used in this thesis is 1.0 (one ship length), and the distances were considered the same for both ships. This is not a necessary condition and may be changed to suit the situation.

Subroutine RBMEAS assumes highly accurate sensors in both range and bearing measuring ability. Such sensors are presently available in the form of Radar altimeters[14] and Laser ranging devices. Another possibility for a measuring method is a single sensor time sharing to obtain range and bearing to both reflectors from a single device. Such a single sensor scheme is sketched in figure III-2.

Once the FWD and AFT parameters are available, they may then be used to determine other desired quantities. Subroutine HDGRAS (HeaDing control for RAS) was developed to output the desired heading corrected for heading difference of ship A and B and the projected correction for distance error. This subroutine is listed in appendix A. The center range and bearing are the average of the FWD and AFT range and bearing output from Subroutine RBMEAS.

The additional heading due to distance is projected as if ship E maintained its present course until it was



perpendicular to the center of ship A. The reasoning behind this is illustrated in figure III-3. If the present course will cause ship B to arrive on the station desired (DS), no heading change is required. The expression for PSIADC ( $\Psi$  Additional heading due to Distance Correction) is:

$$\text{PSIADC} = \text{RSENS} \cdot (\text{DDC} + \text{DA} \cdot \text{SIN}(\text{AA1}))$$

where:

RSENS = Range SENSitivity gain

DDC = Distance Desired Corrected for side of approach

DA = center Distance Absolute (range)

AA1 = 360 degrees - relative bearing of center position

The heading difference of ship A and B is desired since, even if the range when alongside is correct, a large disparity in heading cannot be tolerated. It is realized that some heading difference (crabbing) is necessary to maintain the distance. This crabbing is due entirely to the pressure forces modeled in chapter II. This heading difference is found by computing the difference in the perpendicular projection between the FWD and AFT measurements and finding the arcsin of this difference divided by the distance between sensors. Figure III-4 indicates a sample of this procedure.

The expression for total desired heading is given as follows:

$$\text{PSIDES} = \text{PSIADC} + \text{WTSENS} \cdot \text{PSIDIF} + \text{PSIE}$$

where:

PSIDIF =  $\Psi$  additional heading due to heading DIFFerence

WTSENS = WeighTEd heading difference SENSitivity gain

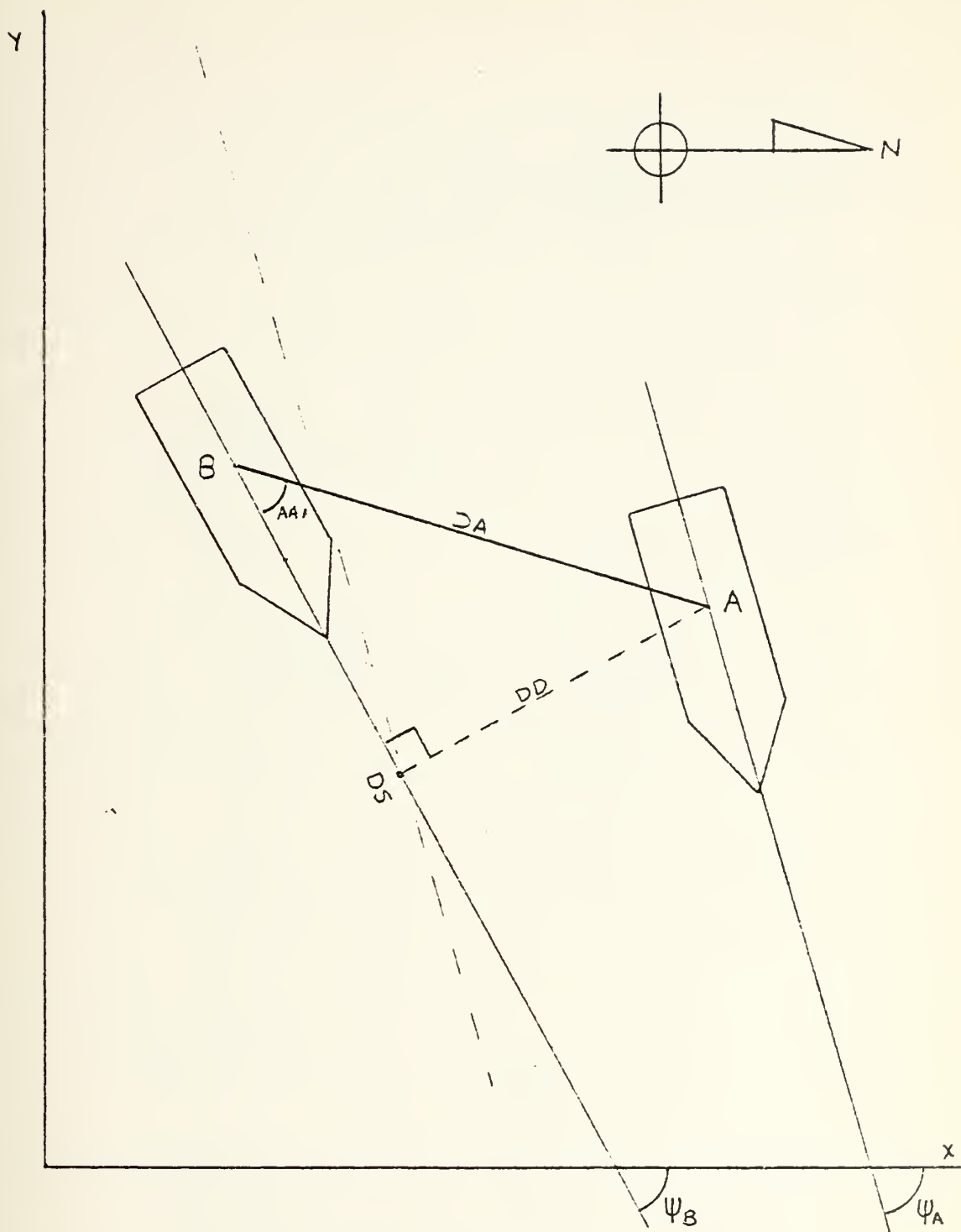


Figure III-3  
Distance Logic

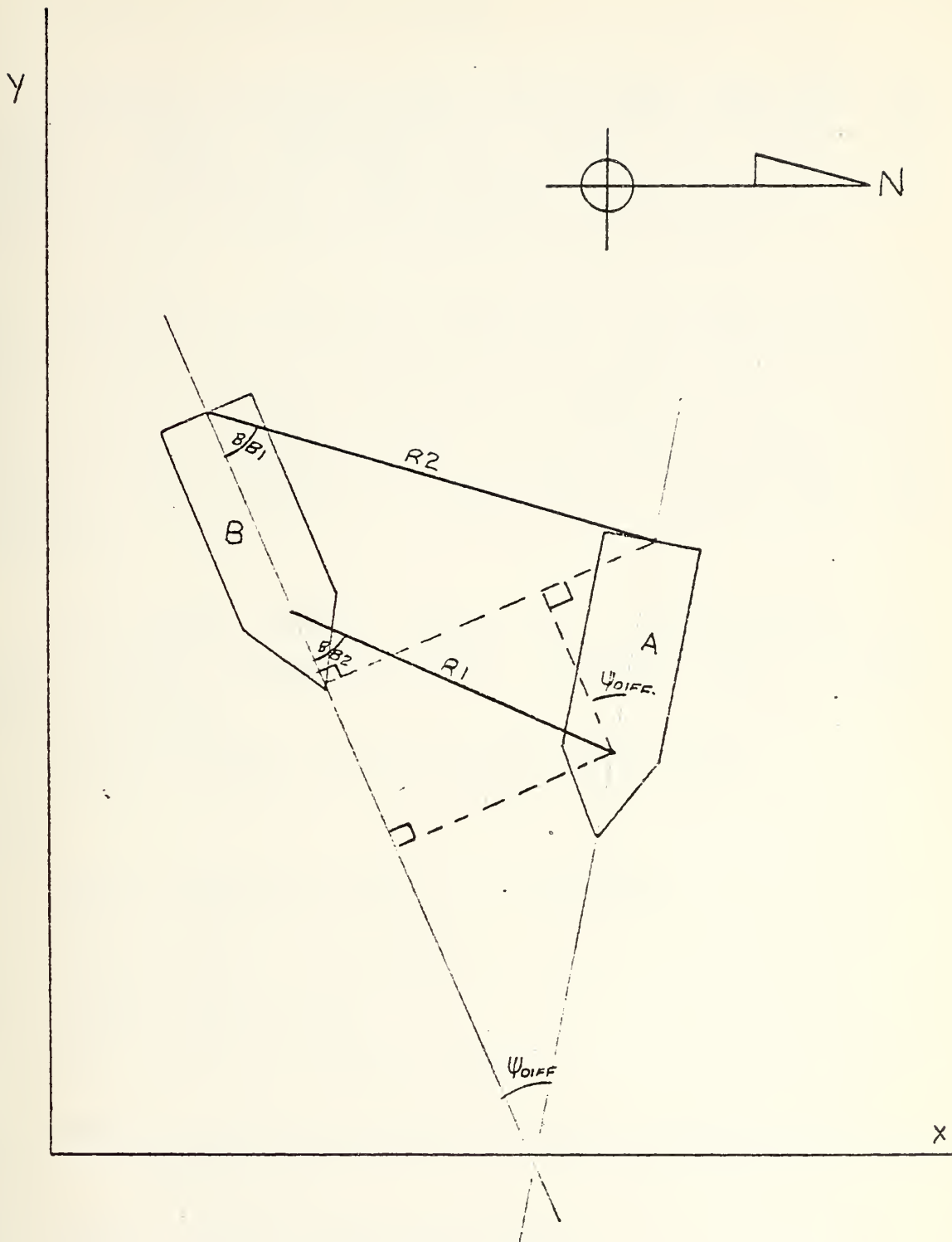


Figure III-4  
Heading Difference Calculation

PSIDES =  $\psi$  (heading) DESired

Throughout the subroutines and main DSL programs, the Function DEGRAD (conversion of degrees to radians and radians to degrees) is used freely. An explanation and listing of this function are presented in appendix A.

The angular velocity of the receiving ship's head is also of concern in the RAS situation. This quantity may be thought of as similar to tachometer feedback in a simple servo control system; and is necessary to damp out the response (the responses of this control system without this feedback is presented in the latter section of this chapter).

The desired rudder command is a combination of the desired heading, angular velocity feedback, and a rudder gain as follows:

$$\text{Desired Rudder} = (\text{YAWD2} - \text{PSIDED} + \text{BDOTFB}) \cdot \text{RGN}$$

where:

YAWD2 = heading of ship B (in degrees)

PSIDED = PSIDES (in degrees)

BDOTFB = VFBG • BDOT2D

VFG = Velocity FeedBack Gain

BDOT2D = angular velocity of ship B heading angle (in degrees/sec)

BDOTFB = angular velocity FeedBack

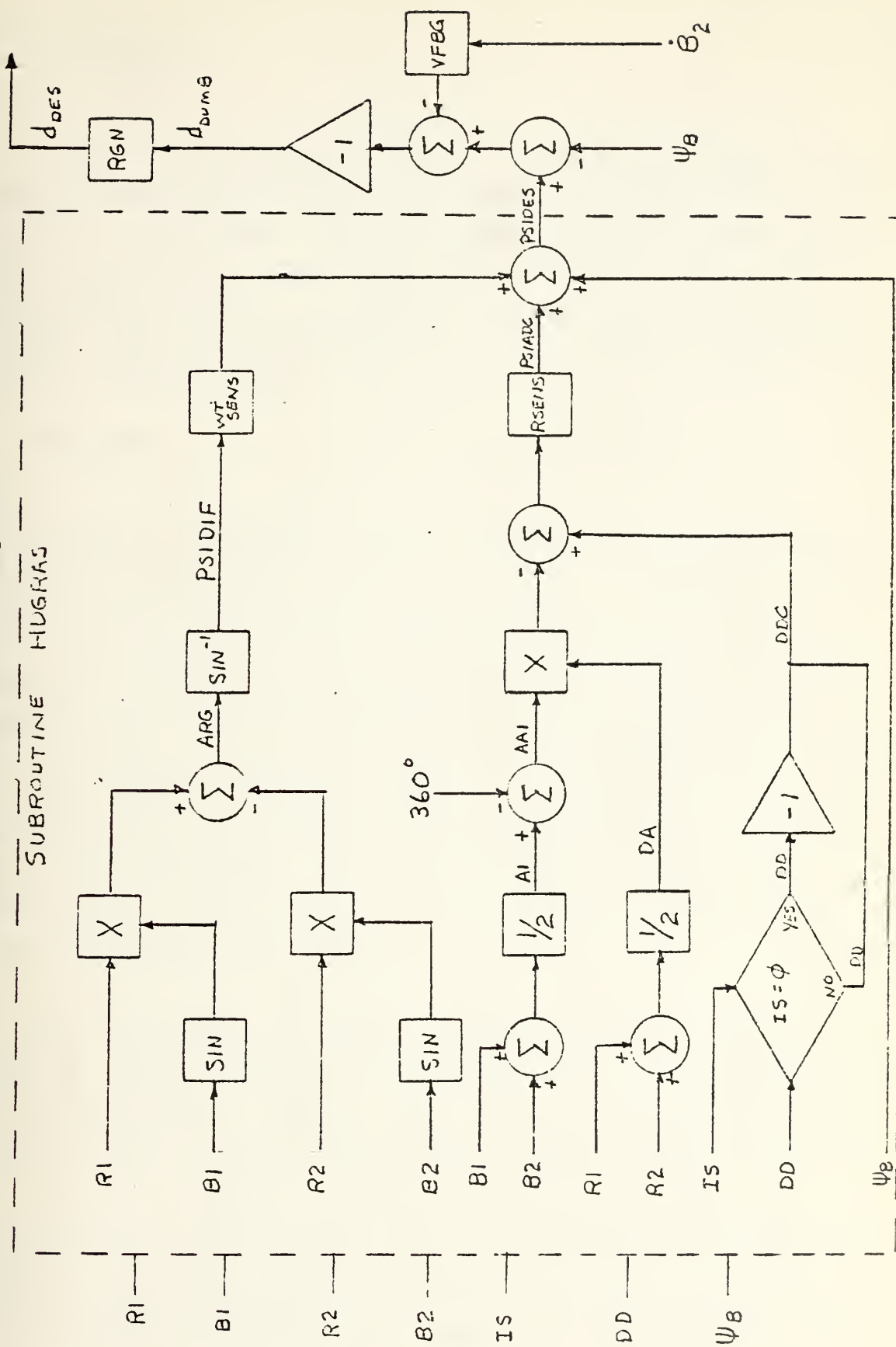
RGN = Rudder Gain

The convention for rudder response dictates negative

rudder as being right rudder, which causes positive yaw. This necessitates making the desired rudder the negative of the forcing function and feedback quantities. The block diagram of figure III-5 presents the control loop from measurement inputs to desired rudder command.

Figure III-5

Rudder Control Block Diagram



### 3. Optimization

Thus far the control choice has identified four gains (RSENS, WISENS, RGN, VFBG) that must be set for proper position attainment. The nonlinear nature of the system which appears in the form of distance measurements, interactive forces and rudder modeling do not allow for straight forward determination of these gains with normal optimal control theory.

#### a. Technique

Grossly nonlinear systems require special handling to determine proper gain settings. The method chosen for this purpose was an optimization algorithm developed by M. J. Box (programmed locally as subroutine BOXPLX). This subroutine, listed in appendix A, was used to locate the cost function saddle point in four dimensional space (the dimensions being the previously mentioned gains). The drawback associated with this method is the necessity of iterating the complete nonlinear simulation within function FE for every evaluation of the cost function. The gains sought were found, but unfortunately only after 2 1/2 to 3 hours of CPU time with every 400 iterations allowed.

The mechanics involved in optimizing the chosen cost function include required sub-calculations in many functions and subroutines. Figure III-6 is a flow chart which demonstrates the steps, subroutines and functions required.

Initial optimization was accomplished for one set of initial conditions. By looking at the RAS situation, a probable set of circumstances were envisioned. The scenario setting is the approach phase where the replenishing ship

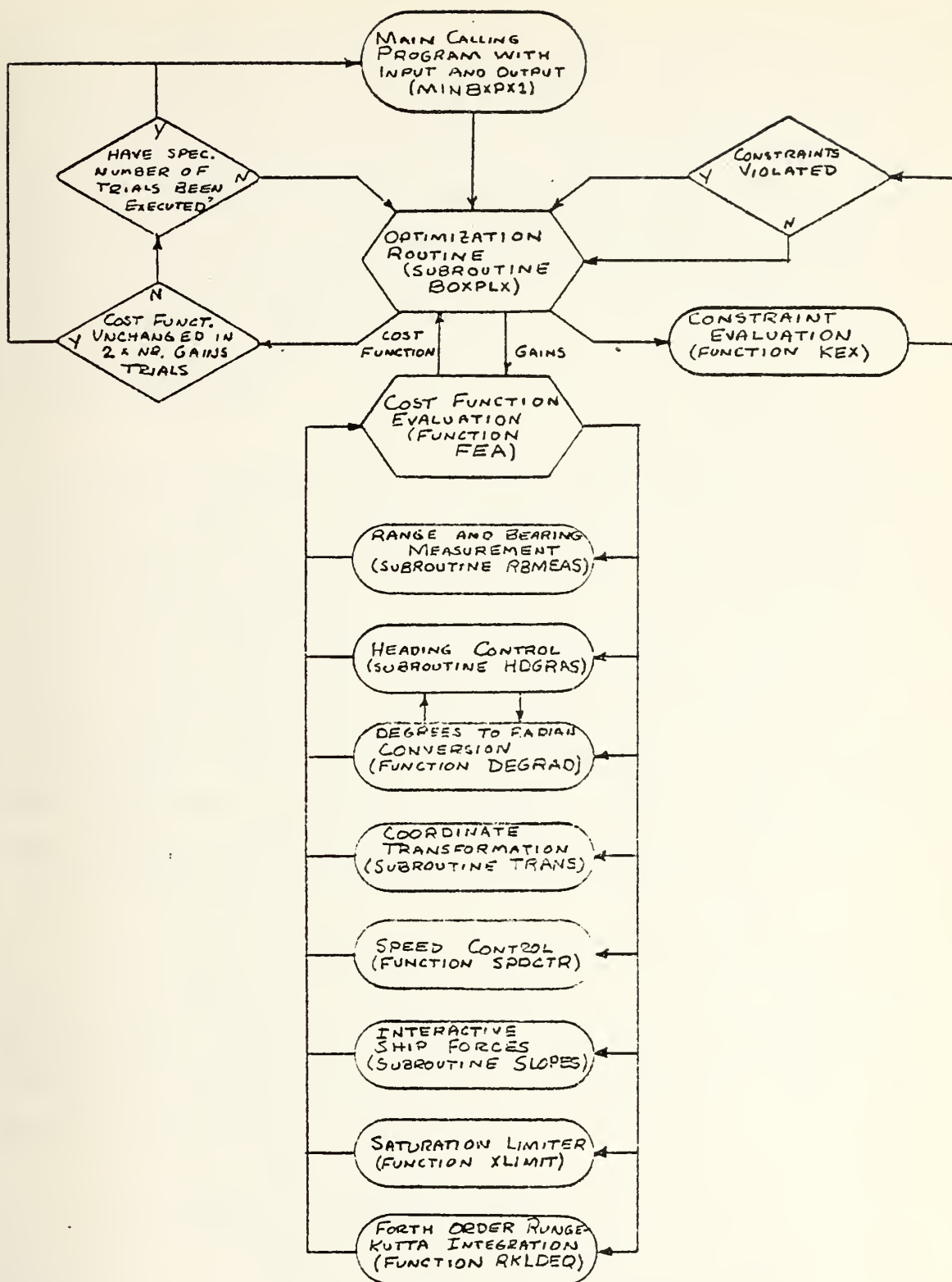


Figure III-6  
Optimization Flow Chart

starts a wide approach at 0.4 ship lengths (211 feet) lateral displacement and 5 ship lengths (2639.0 feet) astern of the supply ship. The desired final position is alongside at 0.2 ship lengths (105.6 feet) lateral separation. Both ships have the same initial heading (YAW angle). The supply ship is at 15 kts. (1.0 normalized speed) and the receiving ship makes its approach at 22.5 kts (speed control will be covered later in this chapter).

#### b. Cost Function

Normal costing of displacement error with the integral of the squared error (ISE) was considered as the optimization tool in subroutine BOXPLX. However, this type of performance measure would weigh the initial displacement error equally with the final position error. This problem can be circumvented by comparing the displacement error to a pre-computed reference track instead of to the desired displacement. For the envisioned scenario, it was conceived that the cost function should weight the distance displacement heavier when the ships are alongside than when the approach is started 5 ship lengths astern.

This was accomplished by using the integral of time times the absolute error (ITAE) as the optimization performance measure. The reference displacement was considered the desired position displacement. The object function can then be written as:

$$CBJ = \int_{t_0}^{t_f} t \cdot |DD - ADY| dt$$

where:

DD = Desired Distance

ADY = Actual Displacement in the Y direction

t = time

A performance measure that is designed to obtain good performance must also take into account other factors besides just position accuracy. Consequently, another cost criterion was decided upon which would also set the gains to reduce the amount of rudder control required when alongside. This particular feature is derived from the desire not to over control with the rudder in such close proximity to another vessel. The inclusion of this term in the performance measure is weighted by unity while the distance accuracy is weighted by a factor of 10.0. This will tend to allow rudder action if the desired position is not maintained. The final approach phase cost function for obtaining optimum gains has the form:

$$CEJ = \int_{t_0}^{t_f} t \cdot (10.0 \cdot |DD-ADY| + 1.0 \cdot |D2|) dt$$

where the additional term is:

$D2$  = rudder response of the replenishing ship

### c. Results

In the process of deciding on the best gain definitions previously mentioned, many optimization runs were made. Each set of gains were then simulated in a corresponding DSL program to obtain performance confirmation. Many of these runs did not live up to expectations; causing re-evaluation of the control scheme until the one presented in this thesis was formulated.

Table III-1 shows the input upper and lower limits of search (EU, EL), starting value guess (XS), optimum gain settings (Output) and associated object function value (CBJ) for 20.0 second normalized time simulation run in function FE. These values were then introduced into the DSL simulation program listed as program #5. The results of this simulation are shown in figures III-7 thru III-12. The

Gain	RSENS	WTSENS	RGN	VFBG
BU	2.0	20.0	50.0	10.0
BL	0.1	0.1	1.0	0.01
XS	1.0	1.0	10.0	1.0
OUTPUT	1.86642	2.3869	23.4185	4.35162
OBJ	60.7103			

Table III-1  
Approach Phase Optimization Results

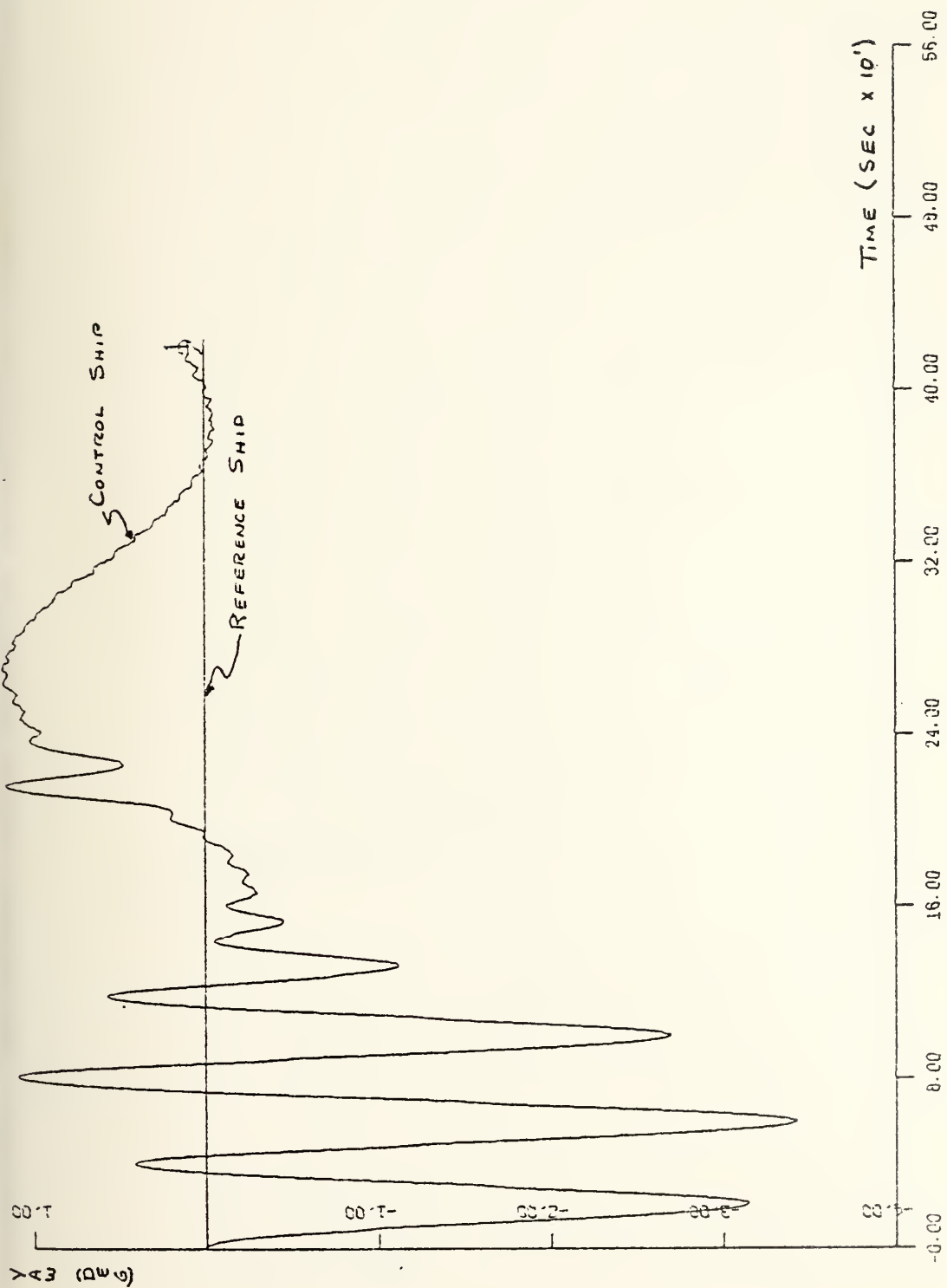


Figure III-7  
Approach Phase Yaw Result



Figure III-8  
Approach Phase Y Forces



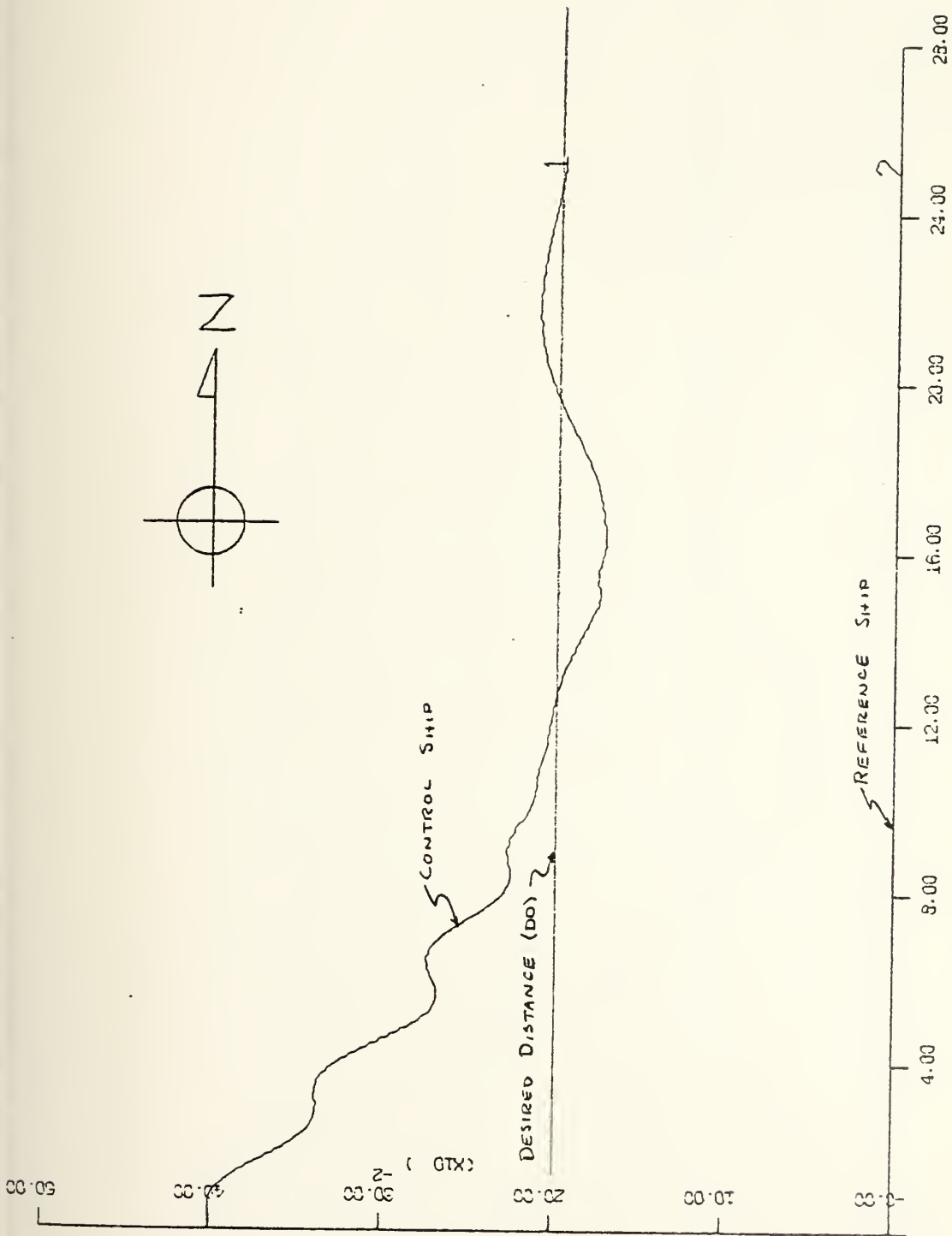


Figure III-10  
Approach Phase Geographic Plot

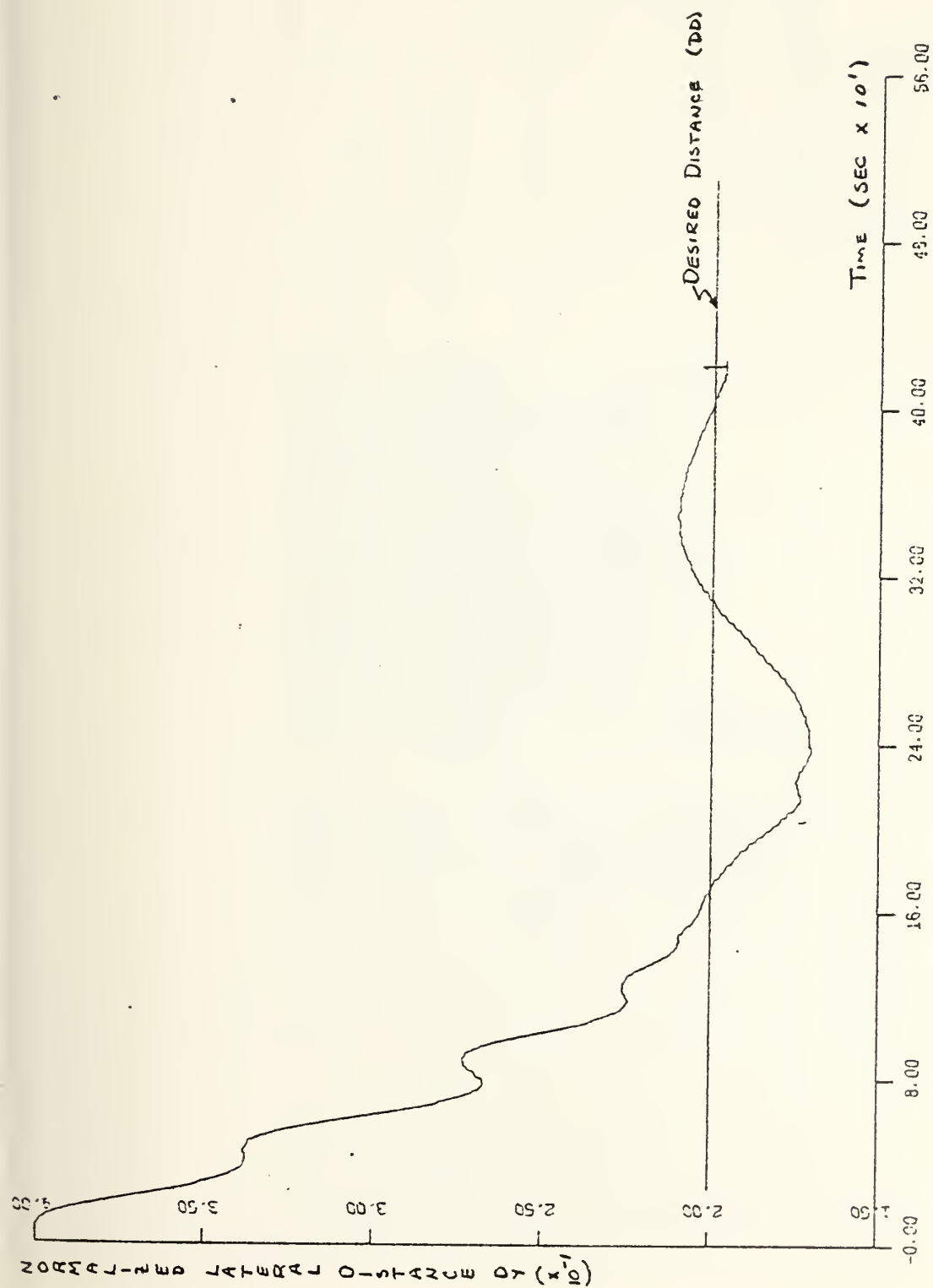


Figure III-11  
Approach Phase Lateral Distance DY

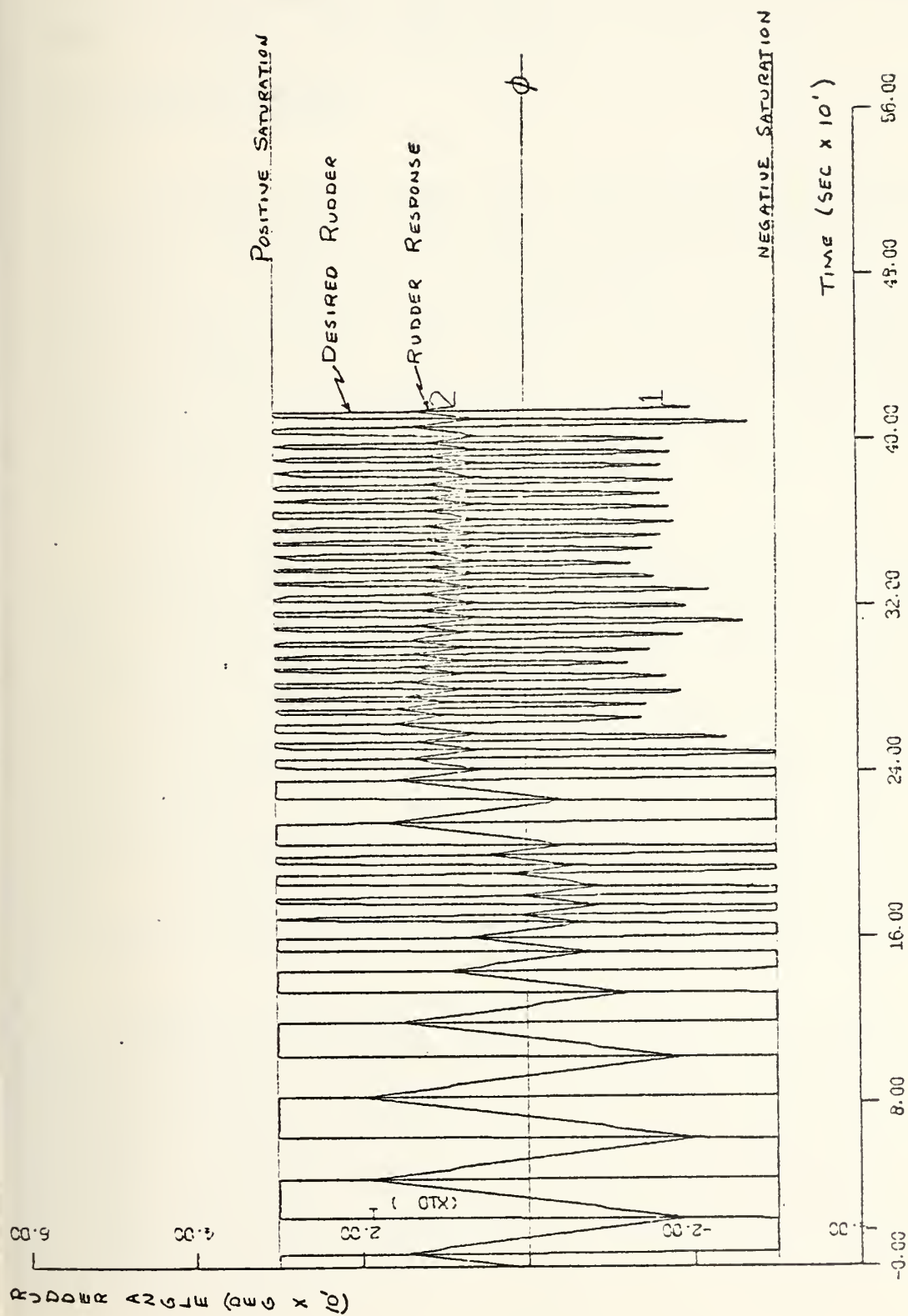


Figure III-12  
Approach Phase Rudder Response

geographic plot of figure III-10 indicates excellent positioning in the lateral direction while the rudder response of figure III-12 shows that it settles out to a fairly constant steady state value as the ship settles into its desired position. The time coordinates in all plots are shown in actual full scale time.

#### d. Control Testing

Now that the "proper" gain settings were obtained, more extensive testing of the control system was required. Three different tests were contemplated: (1) allow a large perturbation turn of the reference ship (supply ship), (2) start approach of the receiving ship (control ship) from different initial conditions of lateral and horizontal displacements, and (3) induce external perturbations in the form of wave forces.

The first test was simulated by turning the reference ship by normal rudder action of figure III-13. This turn with 5 degrees rudder accounted for a total reference yaw change of 15 degrees. The rudder action of the controlled ship shown in figure III-14 was as expected. However, the distance maintainment portrayed in figure III-15 was totally unacceptable. The maximum excursion from the desired distance of 105.56 feet (0.2 normalized distance) was 55.419 feet (0.105 normalized distance). Variances of this magnitude cannot be tolerated in the RAS environment.

Faced with this situation, the tact chosen was to re-evaluate the gains for the new scenario which is called the turn phase. In this phase the initial conditions assume steady state positioning alongside such that the lateral position displacement (DY) is equal to the desired distance [105.56 feet (0.2 normalized)] and that the horizontal position displacement (DX) is 0.0 (alongside).

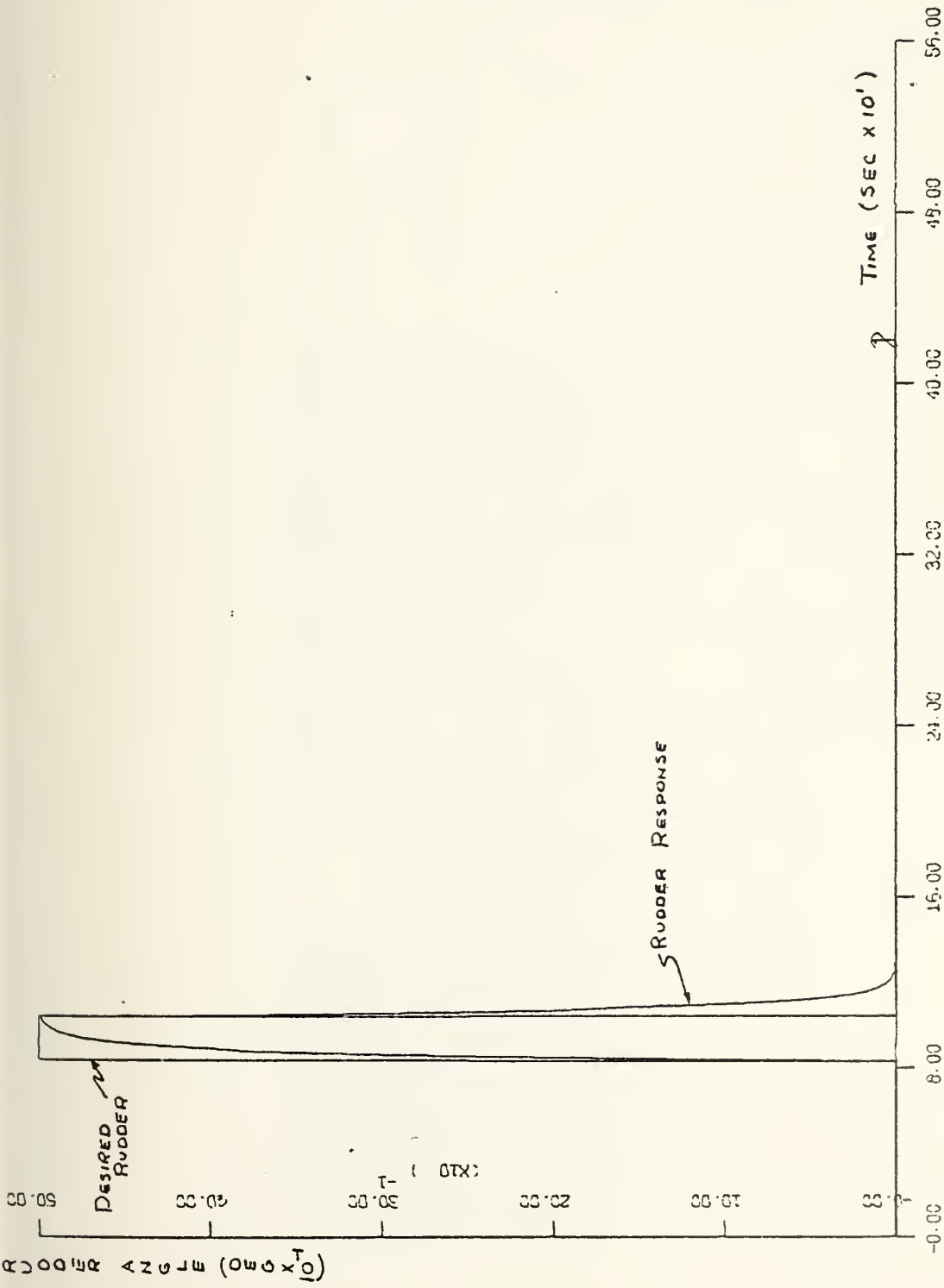


Figure III-13  
Turn Phase Rudder Action of Reference Ship

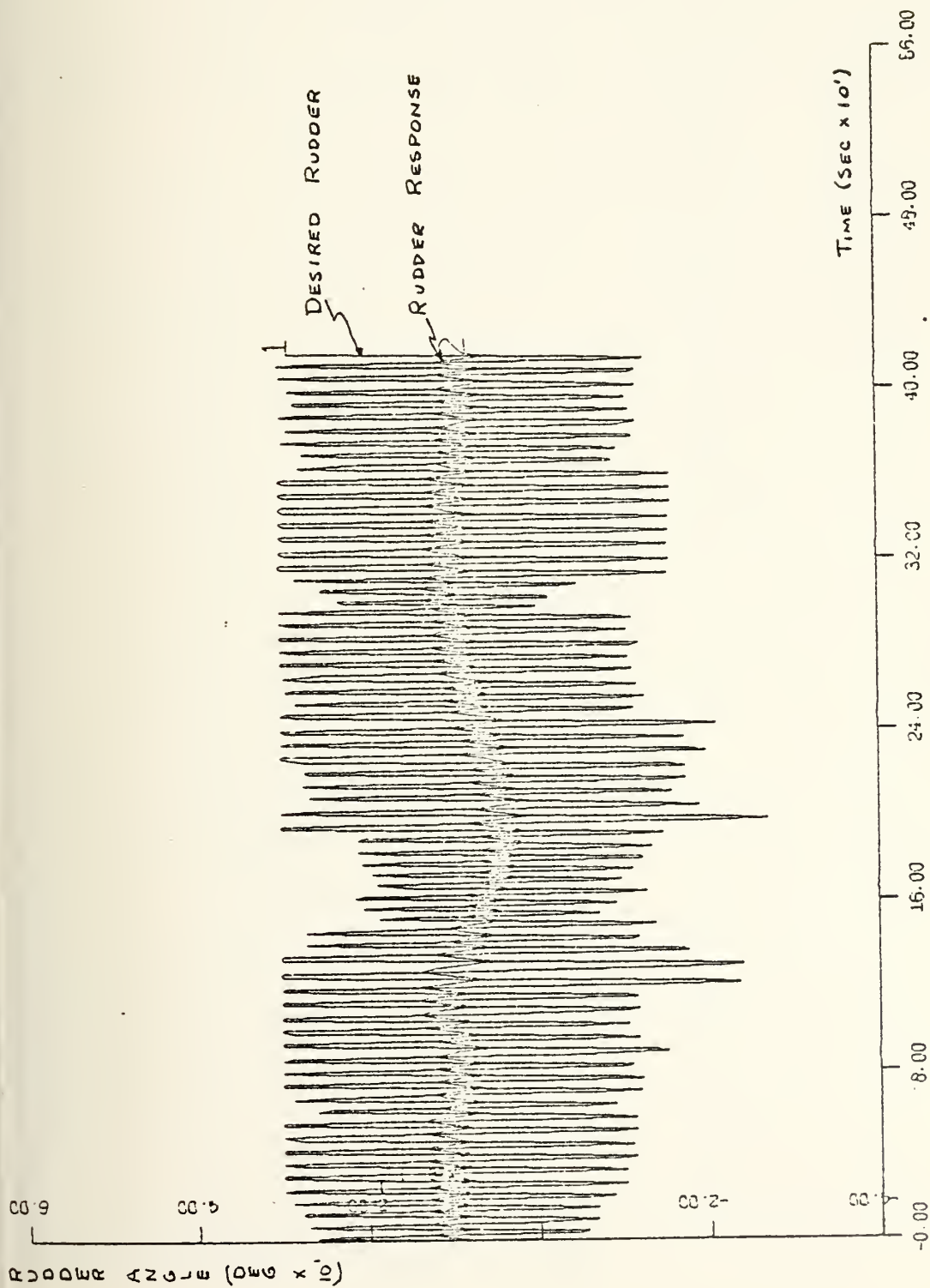


Figure III-14  
Turn Phase Rudder Response

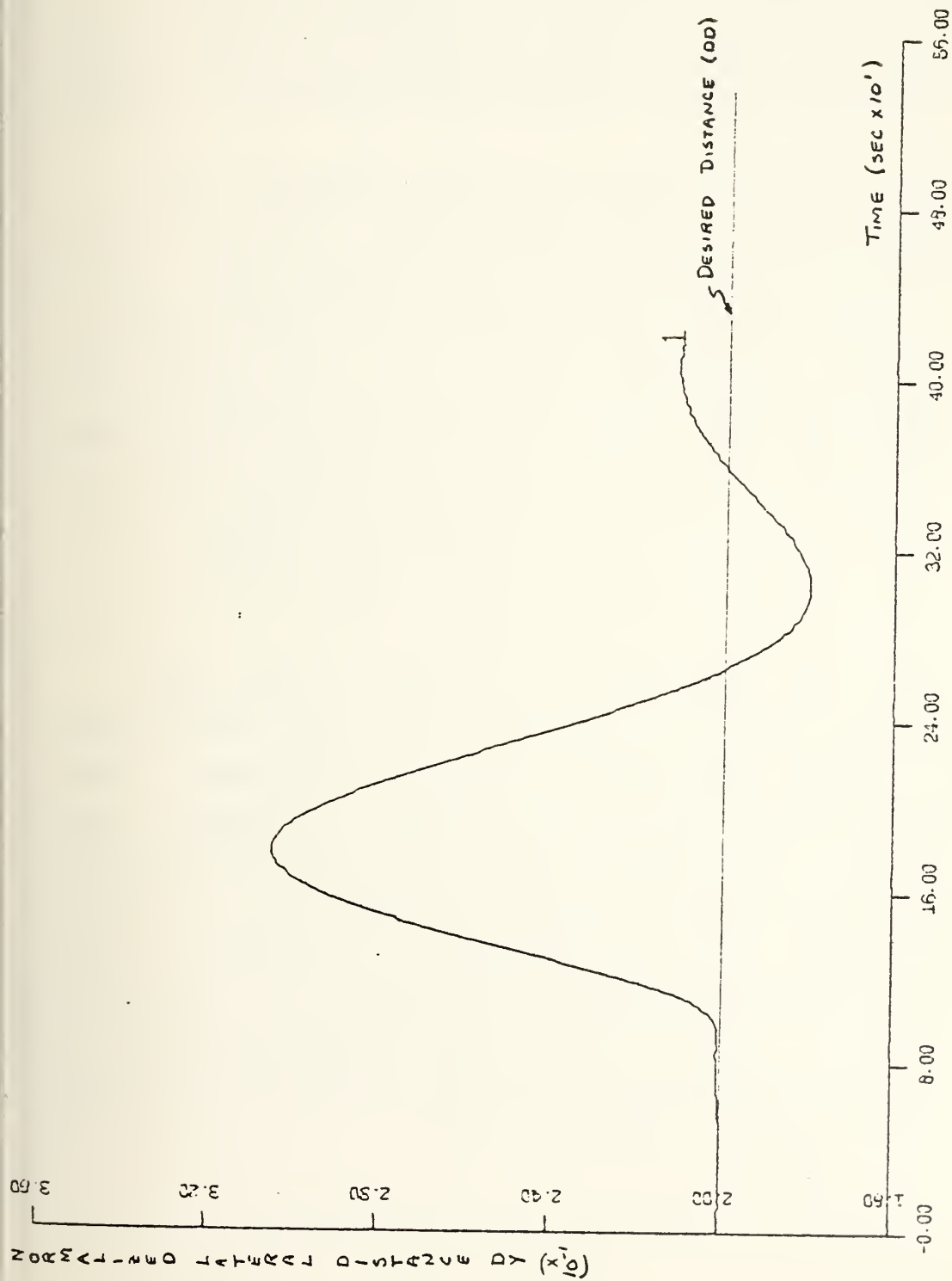


Figure III-15  
Turn Phase Lateral Distance DY

Some initial perturbation is introduced by assuming the relative yaw angle when alongside is negligible.

#### e. second optimization

The same procedure was followed in obtaining gains that would optimize a chosen cost function. Figure III-6 still applies except that function FEA is replaced by function FEB (listed in appendix A) to simulate the new conditions.

Cost function criteria change in this instance since the ships start at the desired position and optimally stay at the same relative positions. Also, the rudder response to such a large turning perturbation must be free to cause achievement of the desired position. Due to these considerations, the integral of the absolute error (IAE) performance measure was chosen for the optimization criterion and can be written as:

$$OEJ = \int_{t_0}^{t_f} |ADY| dt$$

Table III-2 shows the results of the turn phase optimization and the comparison with the approach phase gains. Again DSL simulation was performed using the turn phase scenario. Figures III-16 thru III-21 portray the graphical results. The rudder response of figure III-21 indicates very sensitive response to the interactive forces shown in figures III-17 and III-18. The lateral distance separation of figure III-20 indicates excellent position maintainment with maximum excursion error of only 2 feet (0.0038 normalized). This minimal variation is well within that which can be tolerated in the RAS environment.

Gain	RSNS	WTSNS	RGN	VFBG
BU	2.0	20.0	50.0	10.0
BL	0.1	0.1	1.0	0.01
XS	1.0	1.0	10.0	1.0
OUTPUT	1.99765	0.7357	49.9776	0.084028
OBJ	0.009145			
Approach Phase Output	1.86642	2.3869	23.4185	4.35162

Table III-2  
Turn Phase Optimization Results

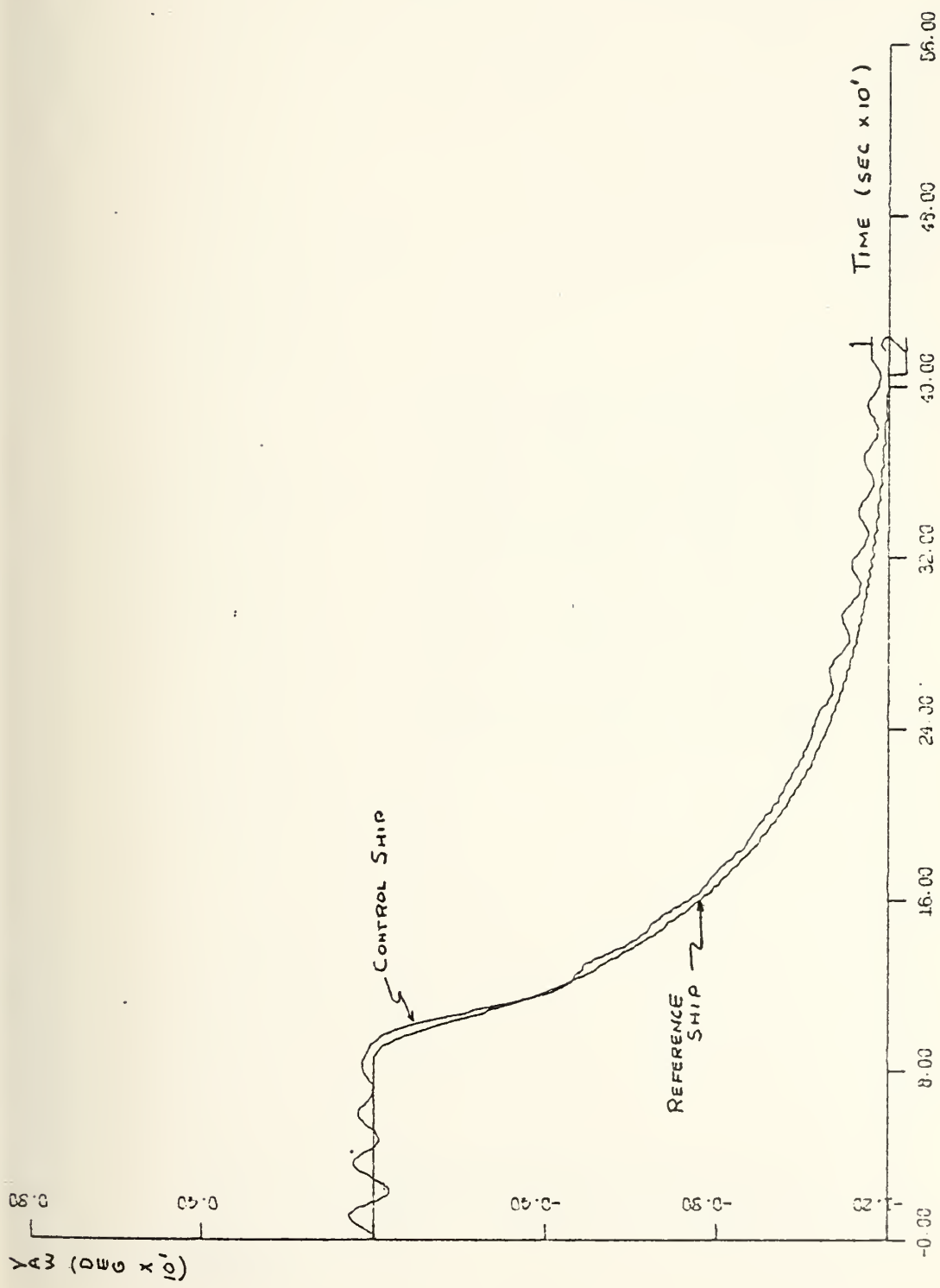


Figure III-16  
Turn Phase Yaw Response

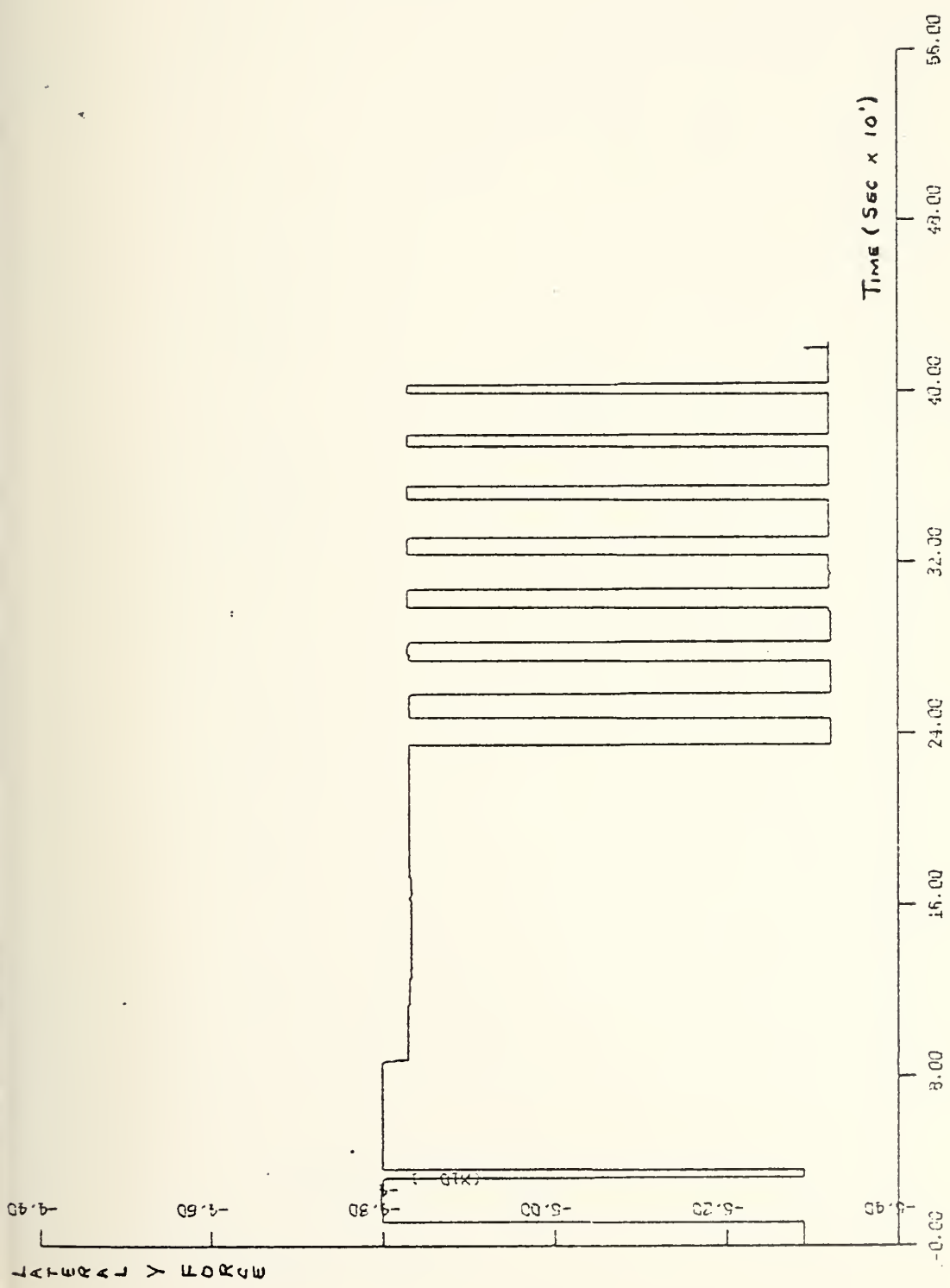


Figure III-17  
Turn Phase Y Forces

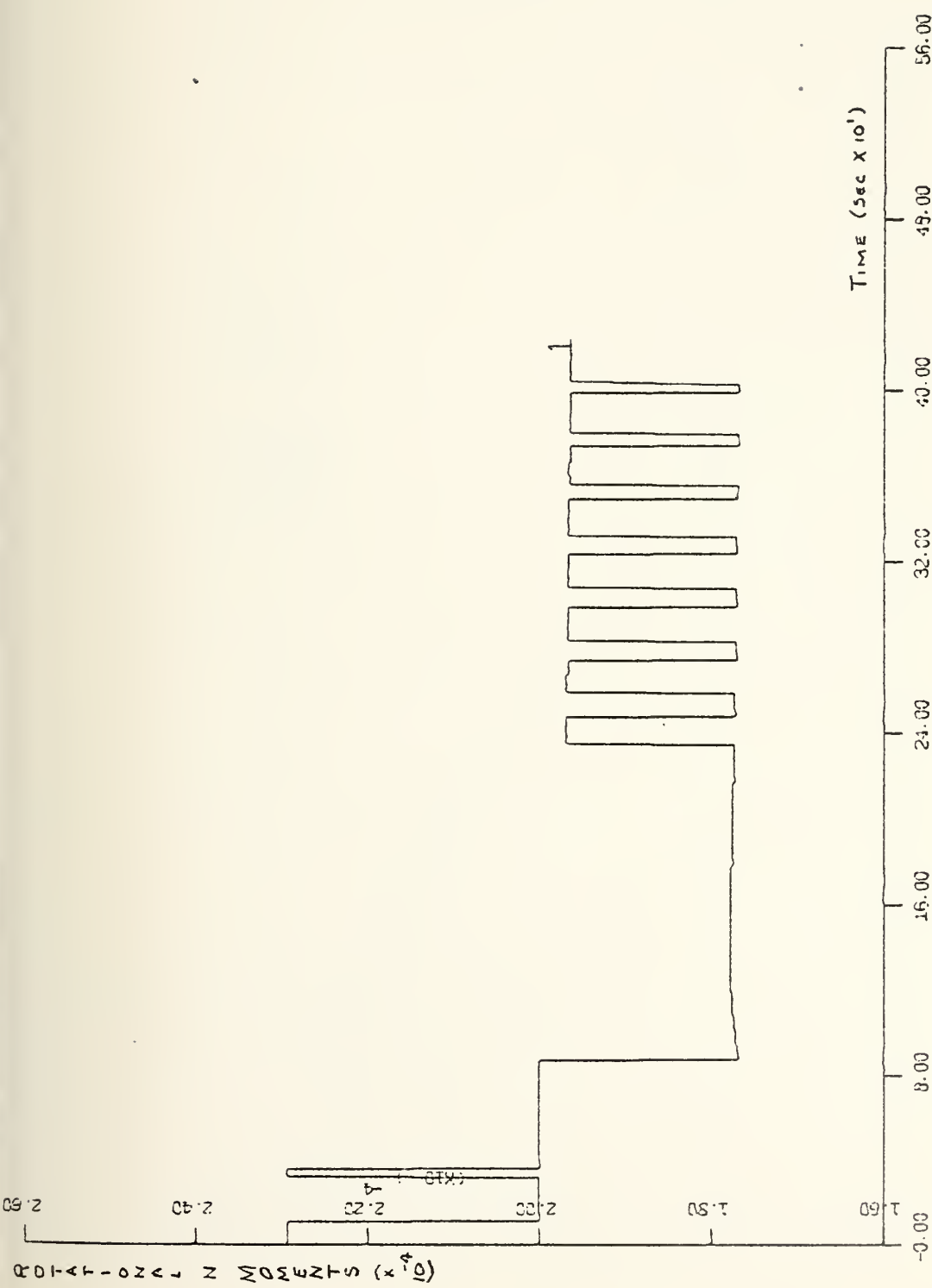


Figure III-18  
Turn Phase N Moments

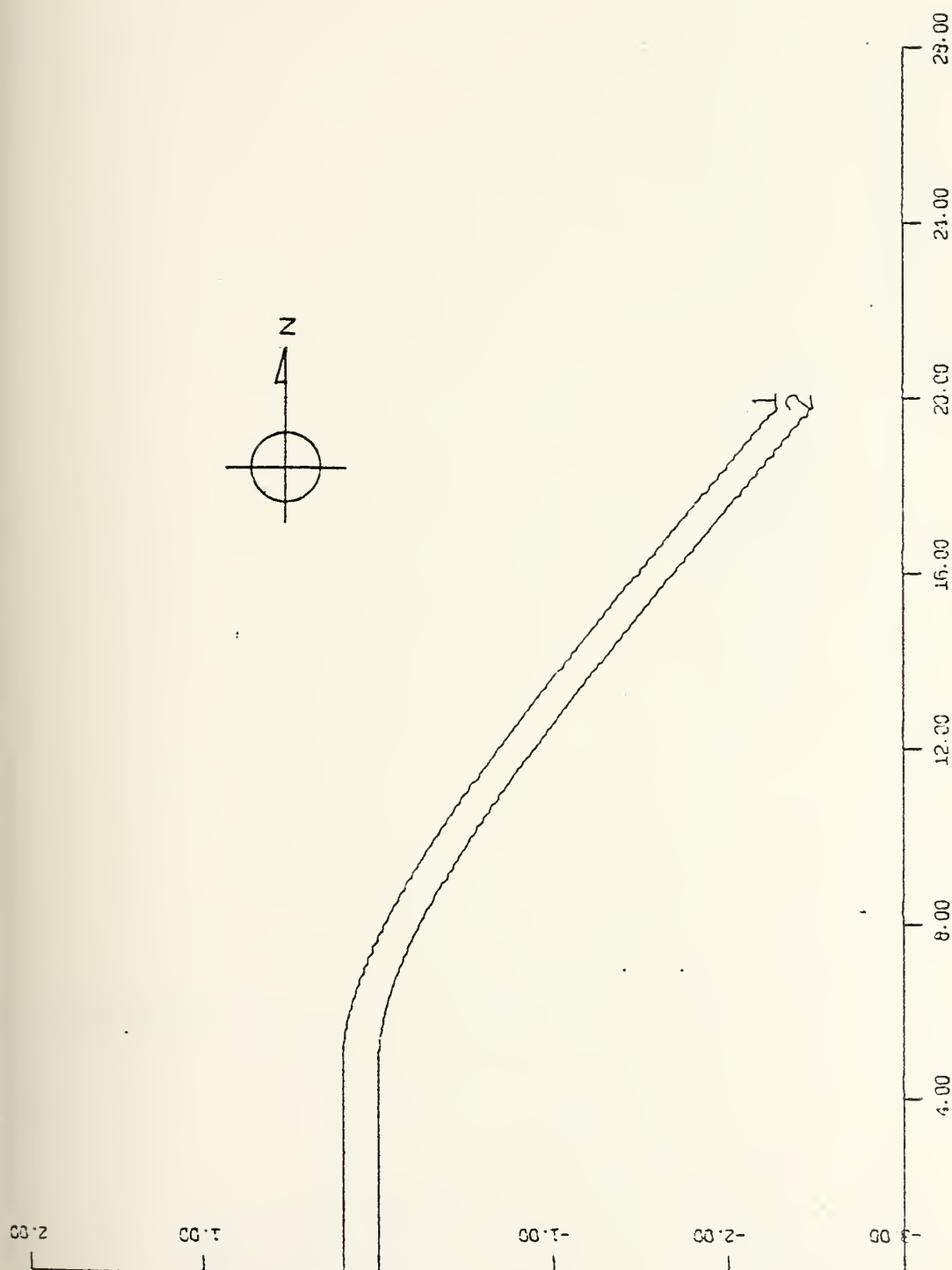


Figure III-19  
Turn Phase Geographic Plot

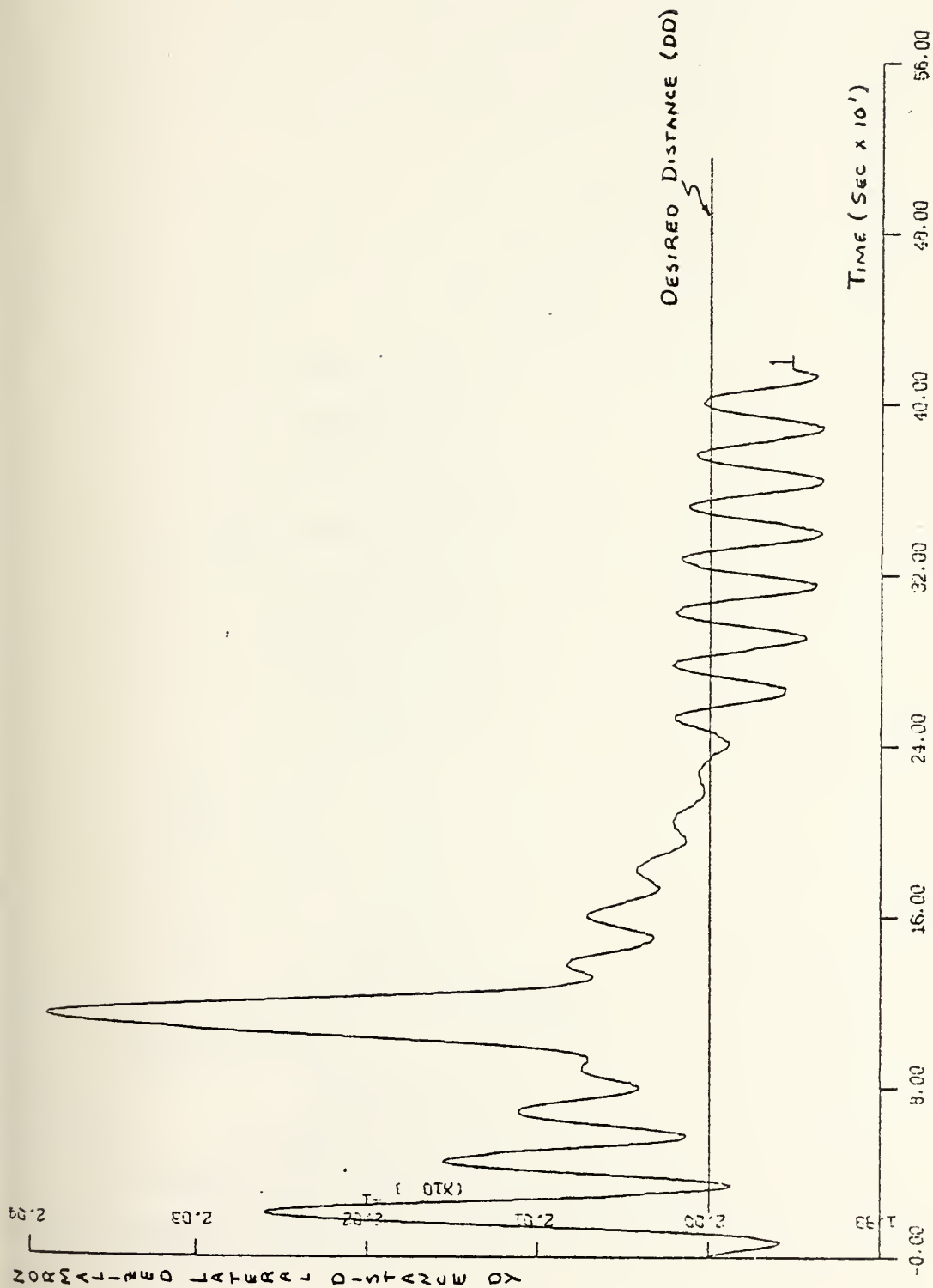


Figure III-20  
Turn Phase Lateral Distance DY

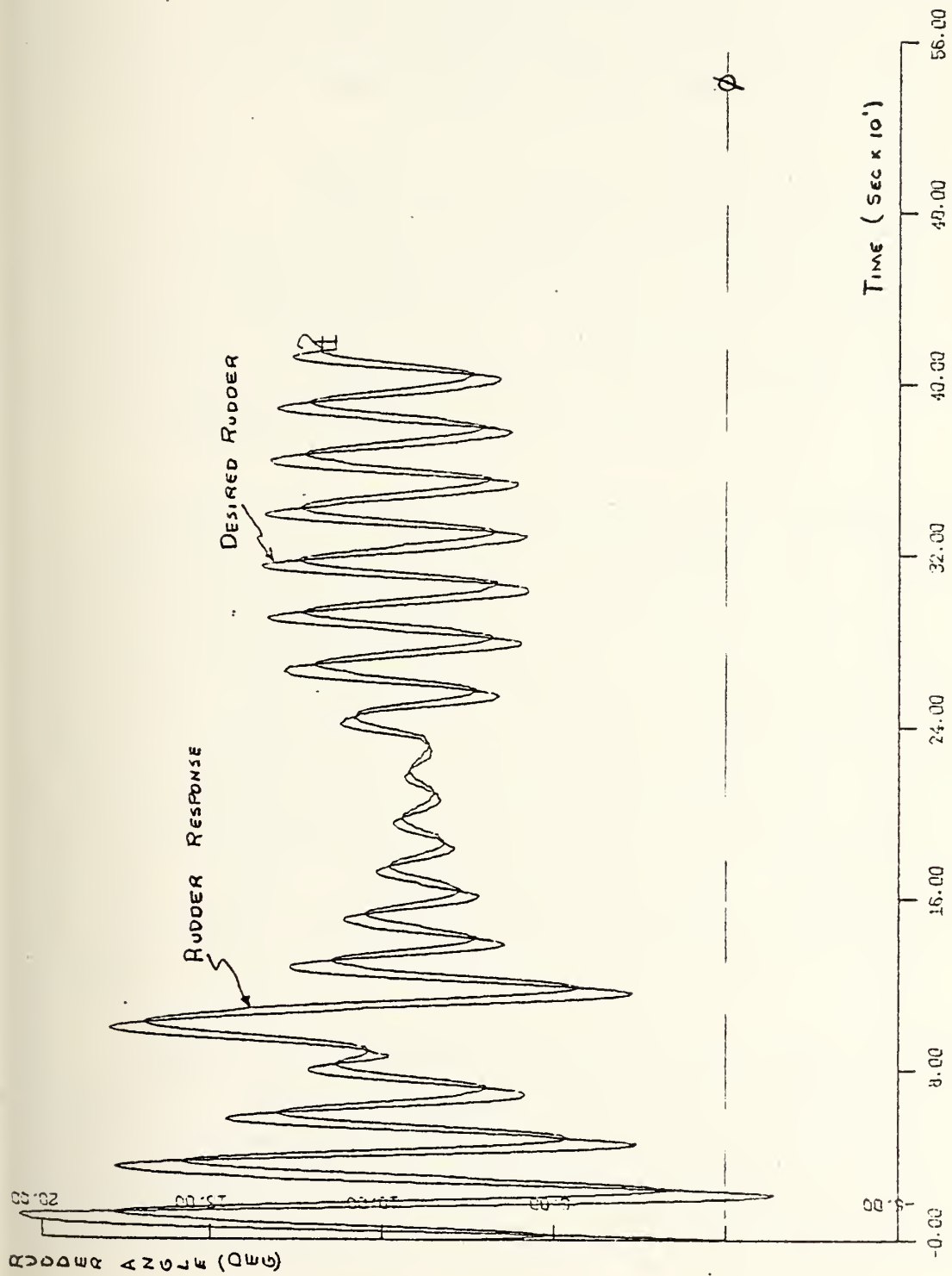


Figure III-21  
Turn Phase Rudder Response

#### f. Continued Control Testing

To alleviate suspicions that the response from the gains obtained in the approach phase could be improved by the gains obtained in the turn phase, a simulation of the approach phase was accomplished with the new gains. Figure III-22 is the graphic display of the effect of these gains on the approach phase lateral distance positioning.

Careful analysis of the results thus far clearly indicate the need for an adaptive control scheme to allow gain adaptation to meet the design specifications. A full adaptive control scheme for systems of this type is outside the scope of this thesis. References 15 thru 23 are indications of some of the literature available for pursuit of a completely adaptive control system.

What was done here is development of a simple algorithm to sense when the conditions were adequate to switch from one set of gains to another. This may be done with the two sets of gains developed thus far. However, for the sake of simulation efficiency, a third set of gains was introduced. This third set amounts to a change of one approach gain (RSENS) which has previously been defined as the range sensitivity gain. The simulation efficiency is increased by decreasing the time required for the approach phase to reach steady state. A consequence of this procedure is a reenforcement of the need for a completely adaptive control scheme.

Repeated simulation revealed that commencing the turn (in effect switching gains), before a reasonable steady state was reached caused results similar to those shown in figure III-22. An increase in RSENS to a value of 4.0 when the lateral separation error is less than 0.05 (normalized)

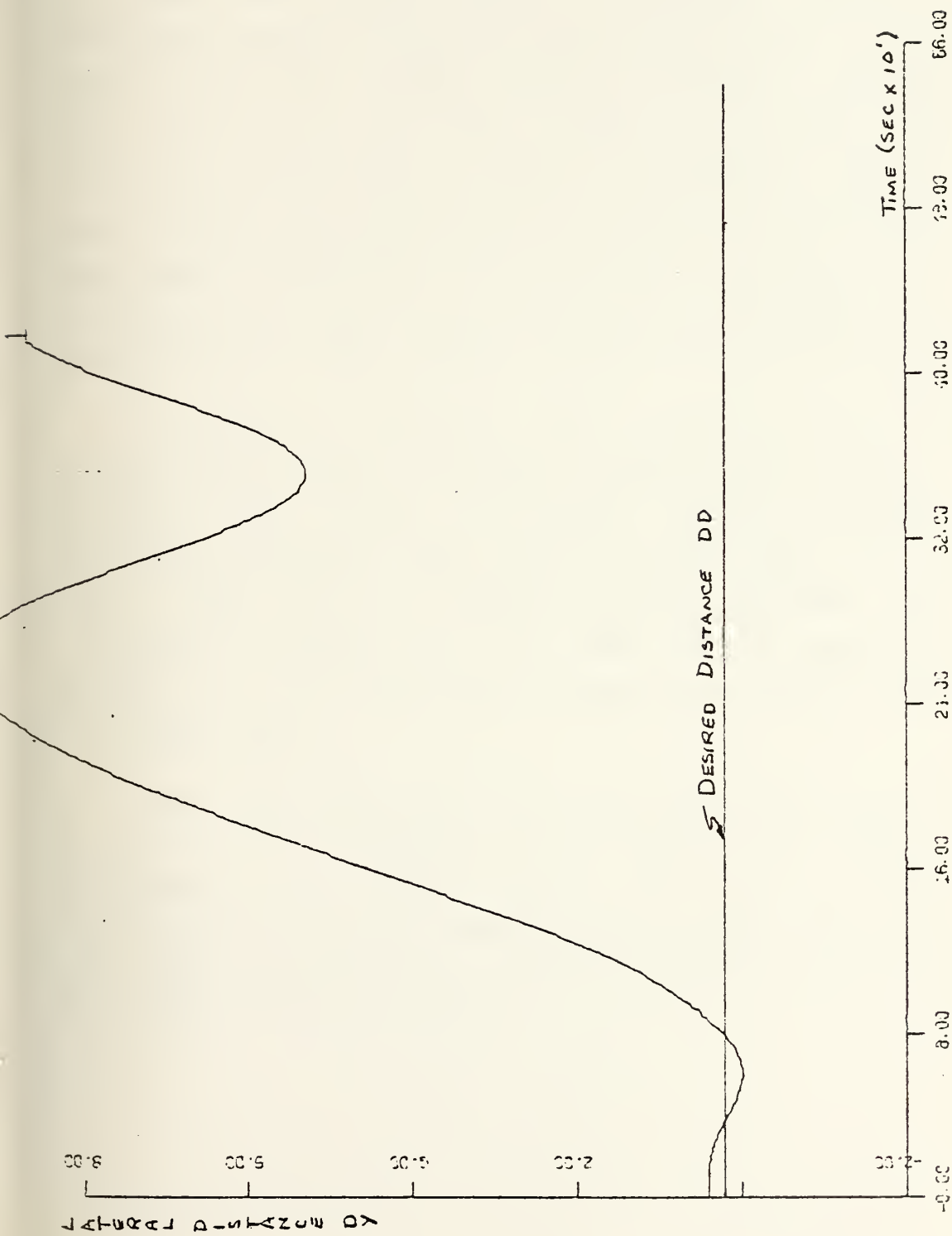


Figure III-22  
Approach Phase Lateral Distance DY

and greater than 0.005 (normalized) forces acceptable steady state in approximately 1/2 the time previously required using a single set of approach gains.

Subroutine SWITCH (listed in appendix A) incorporates this simple adaptive gain schedule with a counter mechanism to sense when steady state is reached. Further study indicated a need to damp the yaw oscillations to a greater extent if the yaw velocity (BDOT2D) exceeded 2.0 degrees/sec when the gains are initially switched to the more sensitive ones of the turn phase. This is an artificial adaptive gain for VFEG caused by computer time restrictions prevalent in a full scale computer simulation where both the approach and turn phases are desired. If the gain switching point is moved up in time, as would normally be the case in a real life situation, this damping increase would not be required.

The results of the full scale simulation using computer program #6 are shown in figures III-23 thru III-34. The approach phase plots of figures III-23 thru III-28 show definite improvement over that previously shown in figures III-7 thru III-12. Figure III-27 indicates that the overshoot is reduced to 10.6 feet (0.02 normalized) as opposed to 17.9 feet (0.034 normalized) that was prevalent in figure III-11.

The turn phase plots are shown in figures III-29 thru III-34 and show responses very similar to those shown previously in figures III-16 thru III-21. The only significant differences occur in the initial responses which are due to the incorrect initialization when the turn phase was simulated individually.

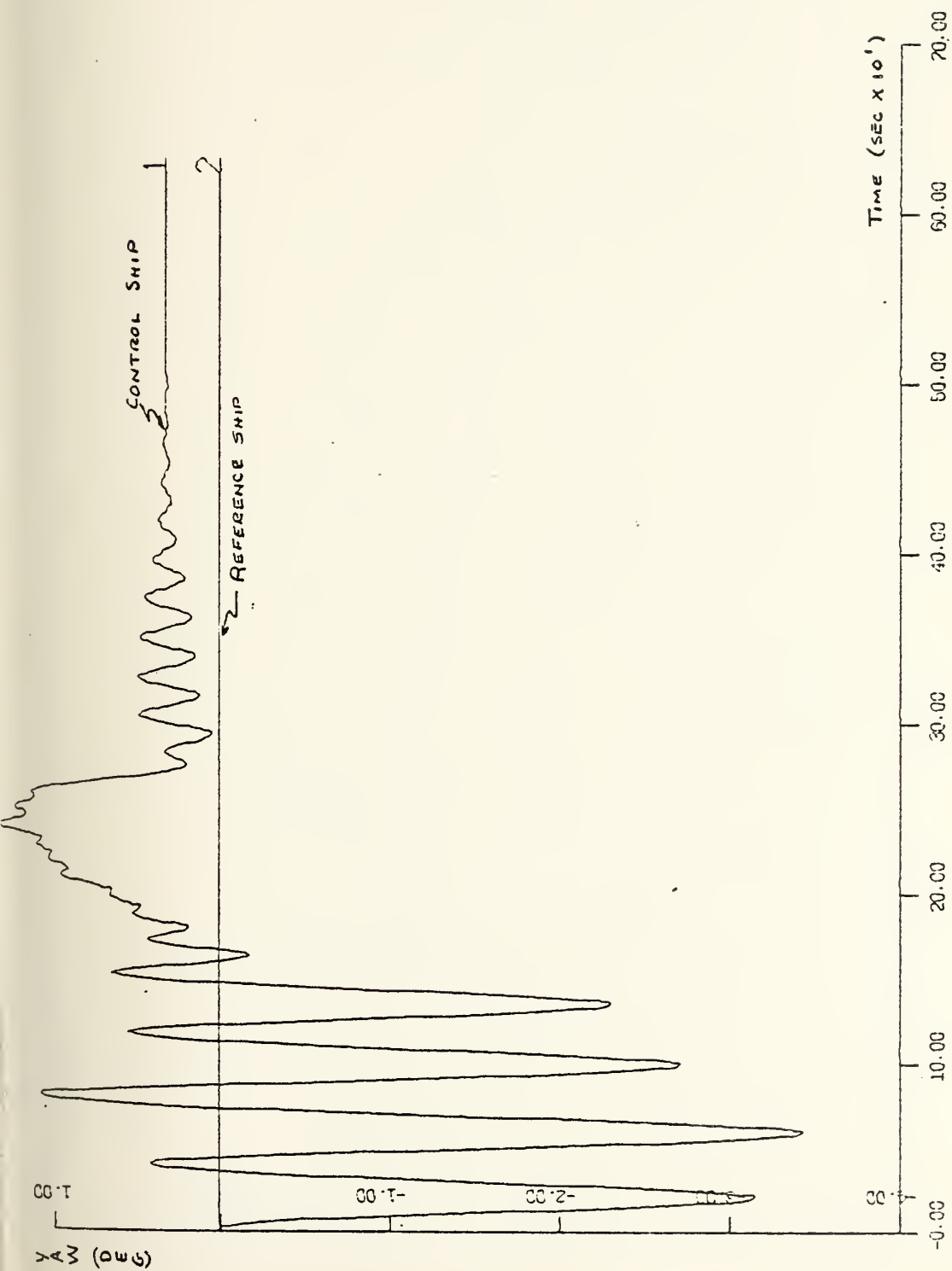


Figure III-23  
Approach Phase Yaw Response

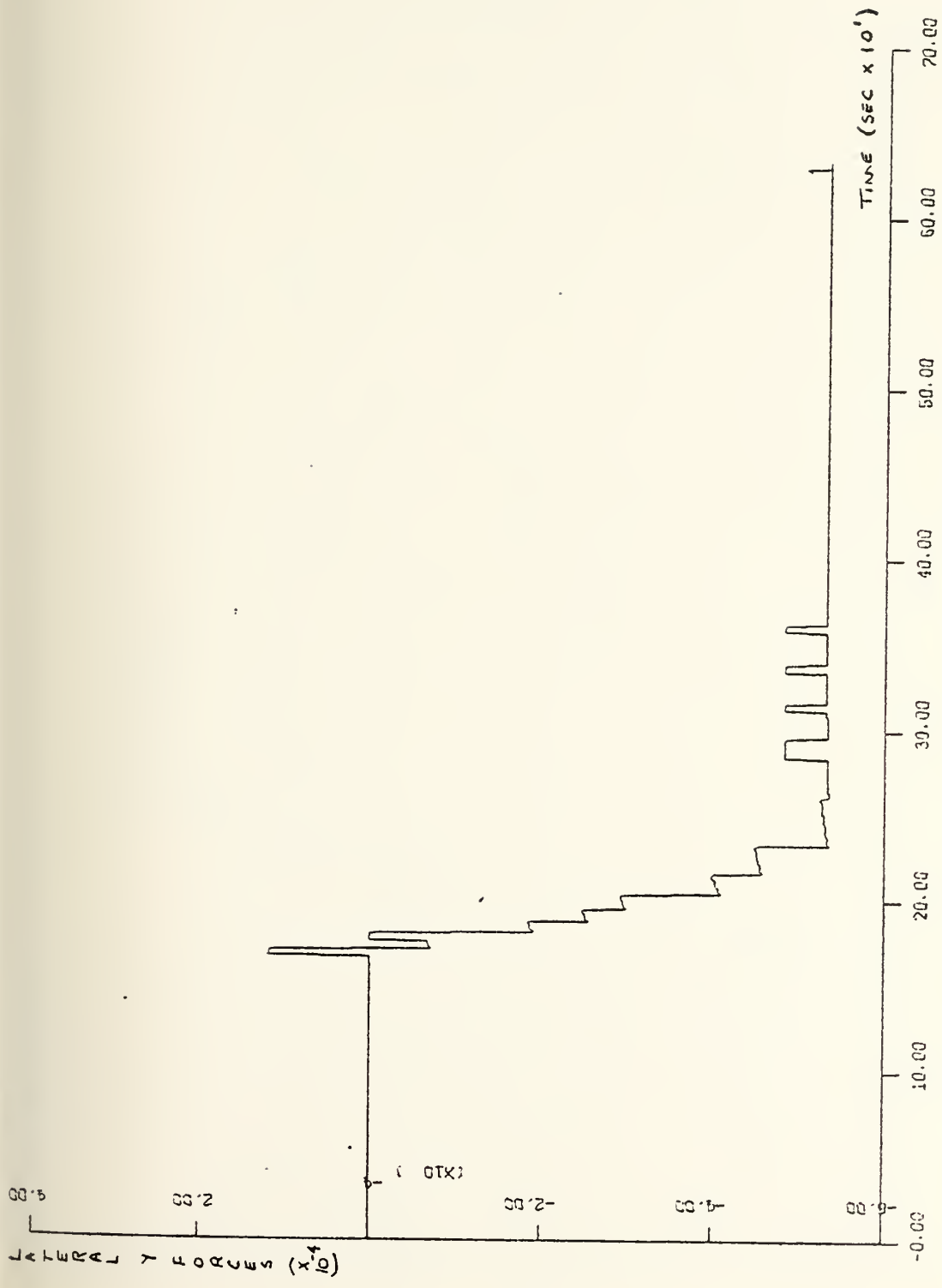


Figure III-24  
Approach Phase Y Forces

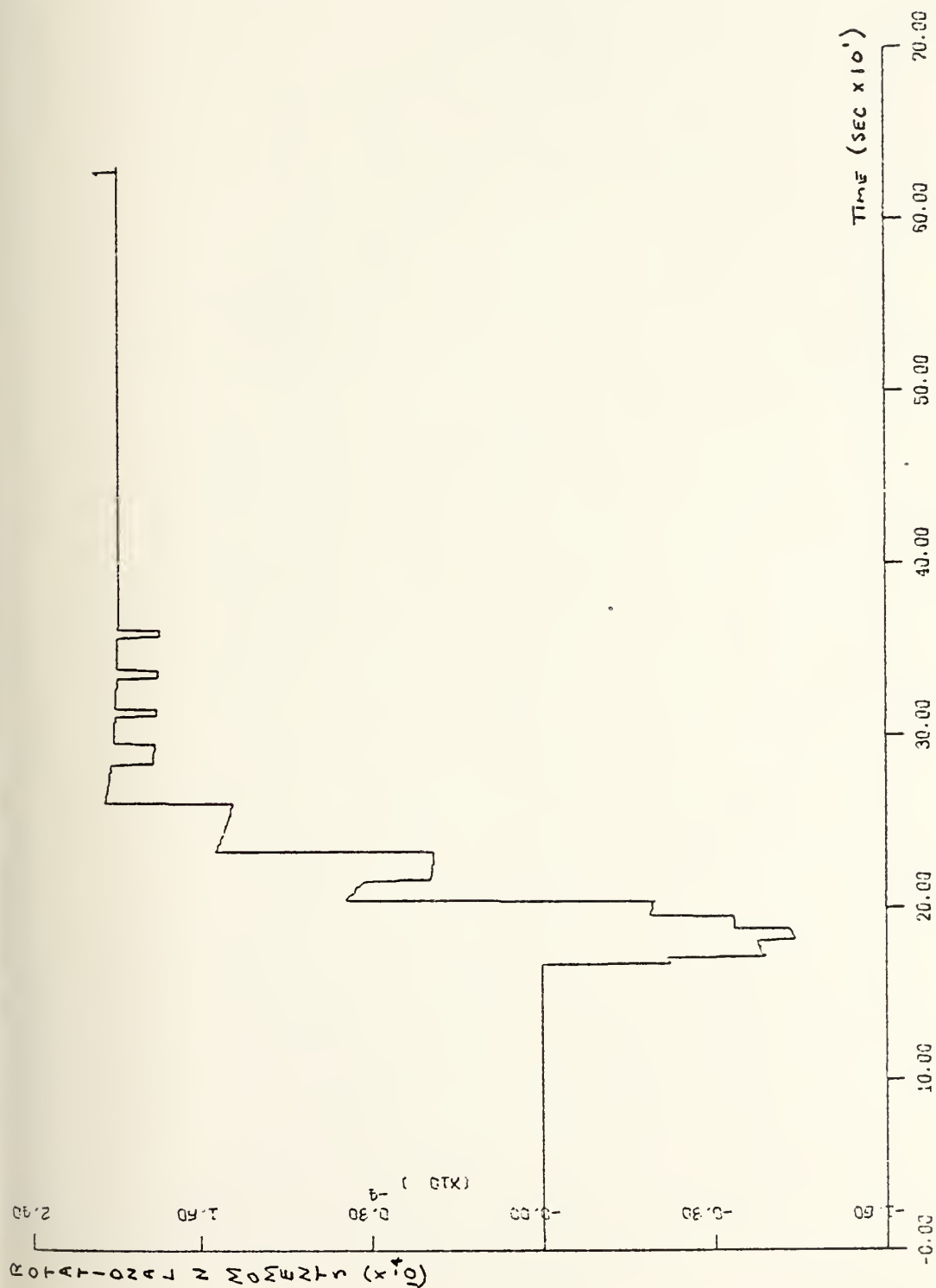


Figure III-25  
Approach Phase N Moments

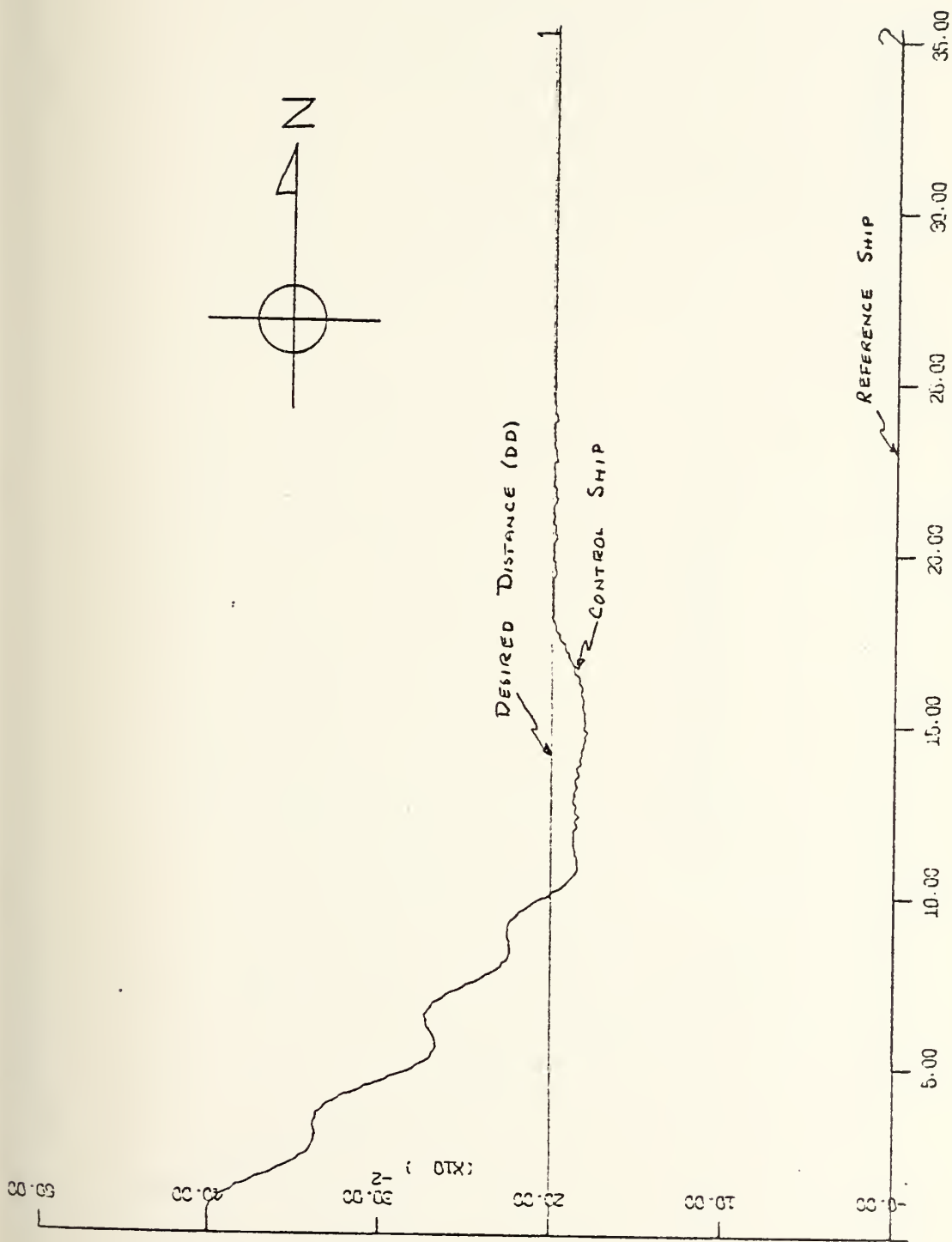


Figure III-26  
Approach Phase Geographic Plot

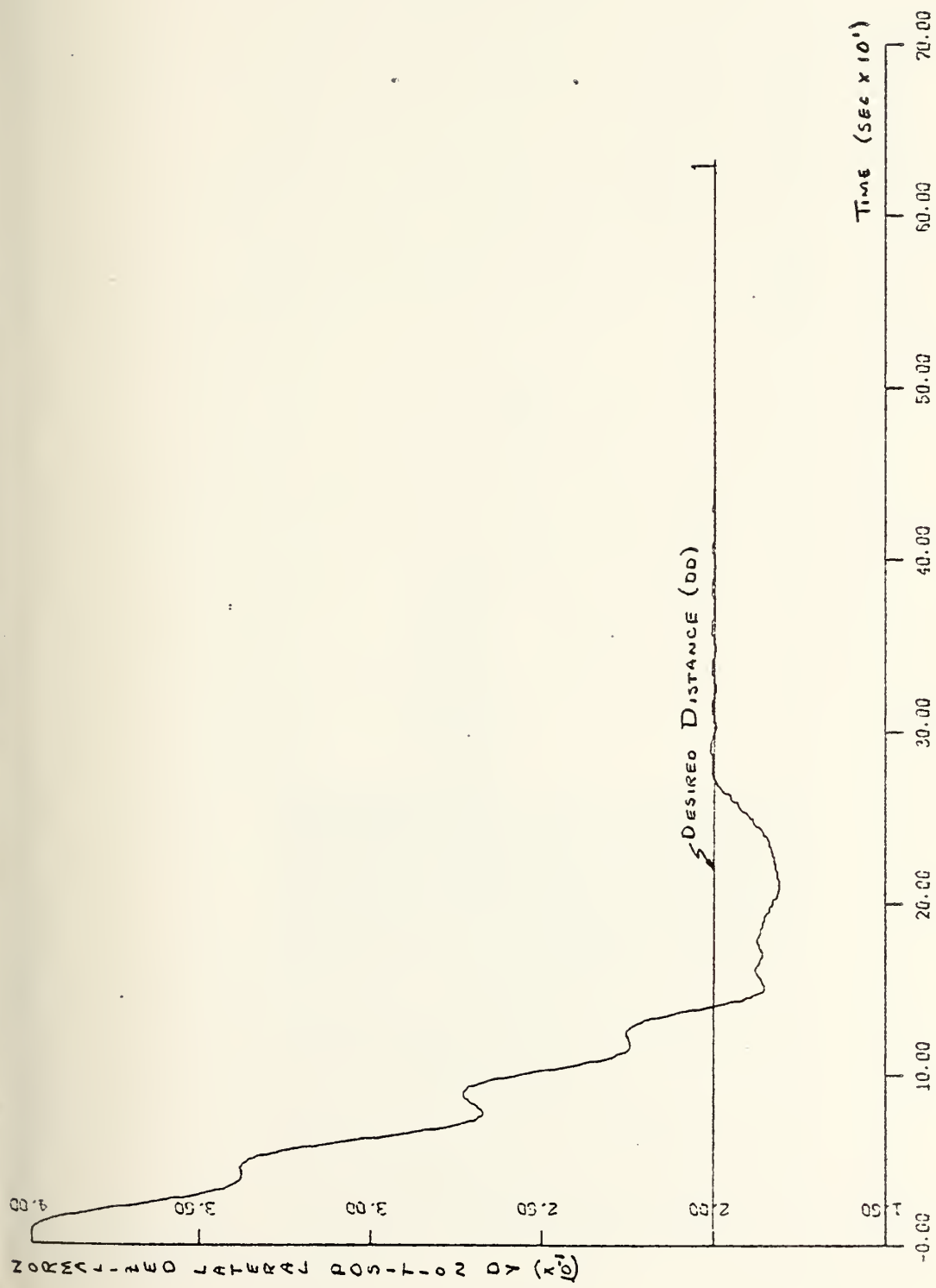


Figure III-27  
Approach Phase Lateral Distance DY



Figure III-28  
Approach Phase Rudder Response

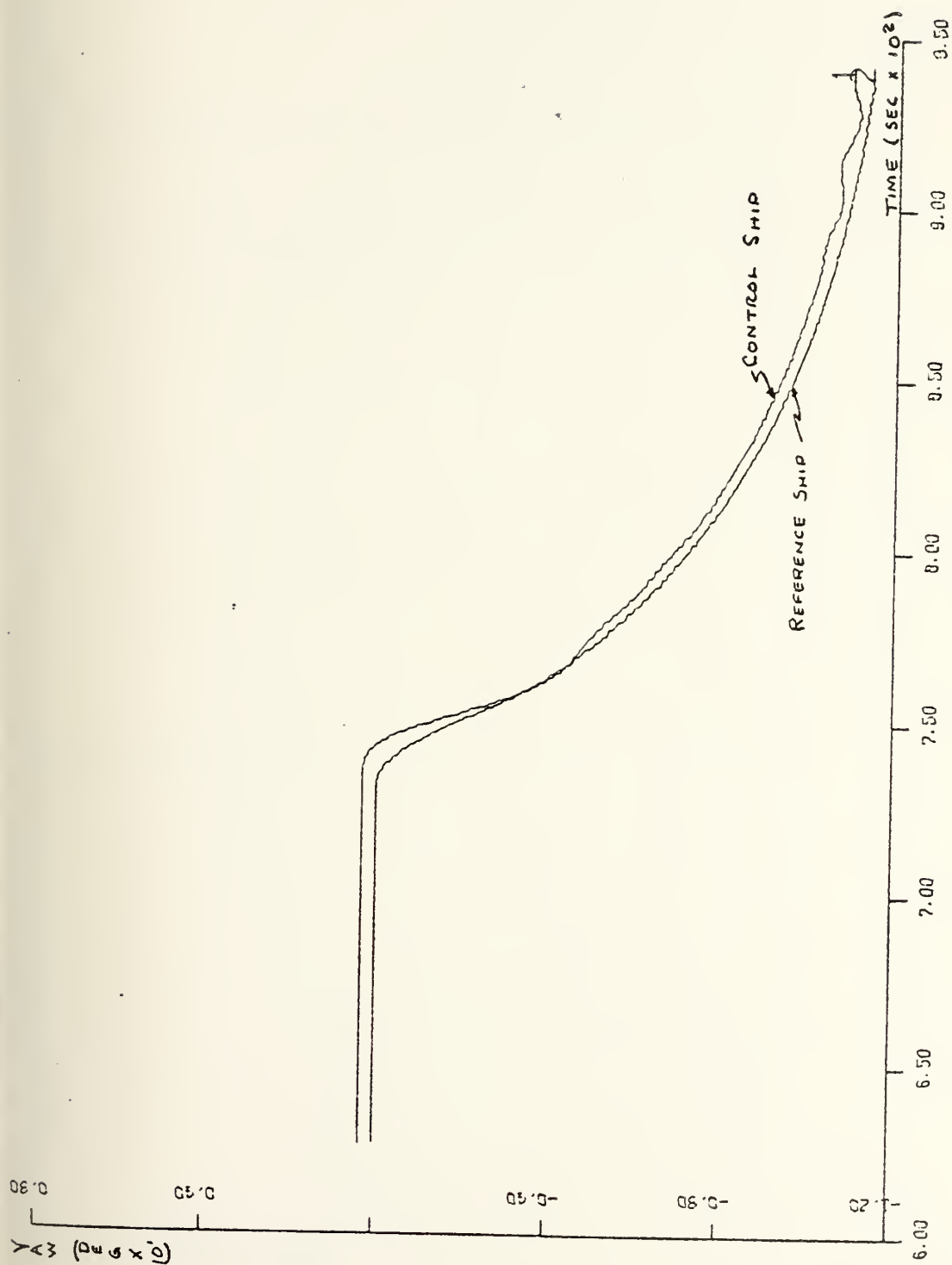


Figure III-29  
Turn Phase Yaw Response

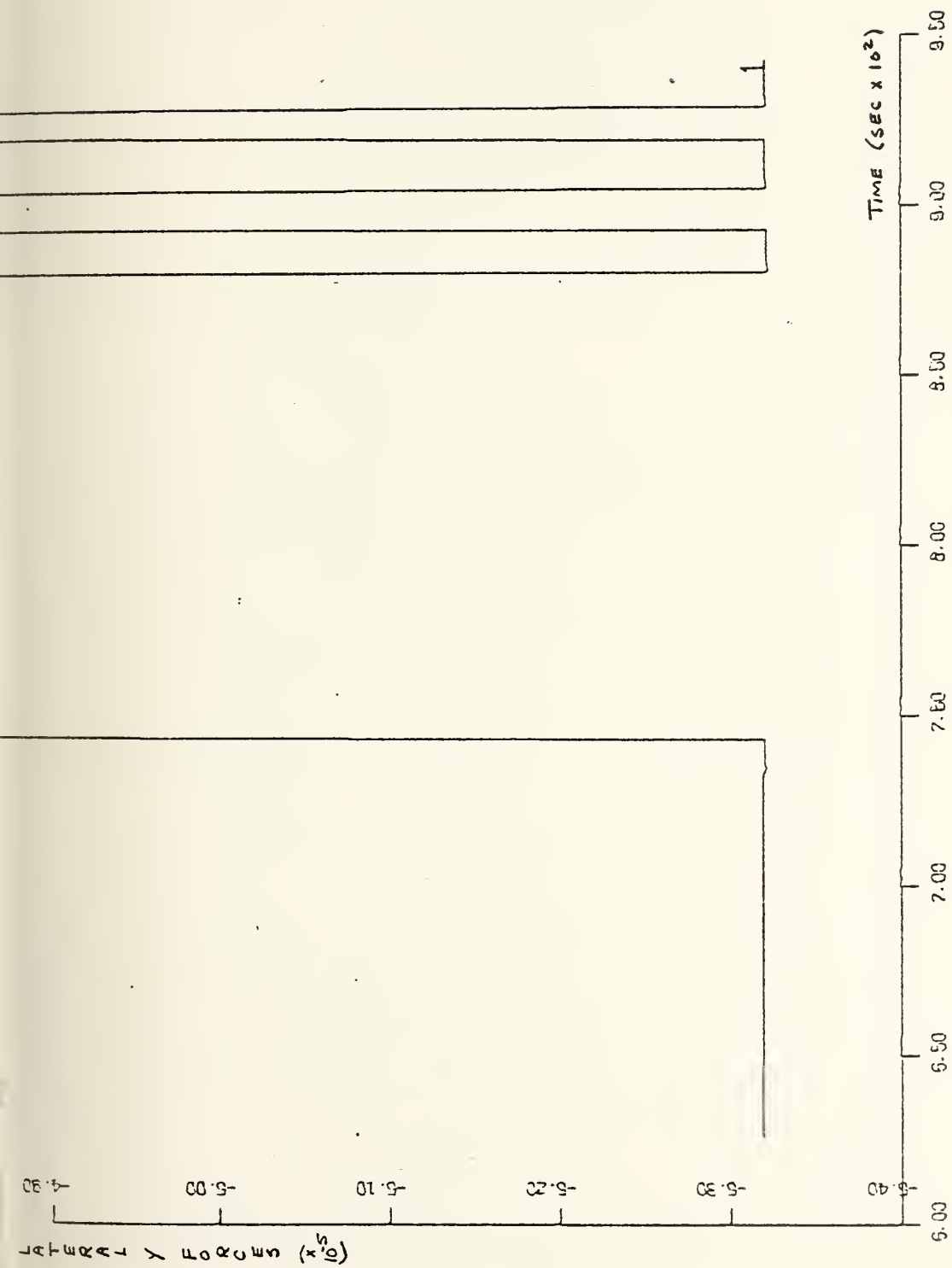


Figure III-30  
Turn Phase Y Forces

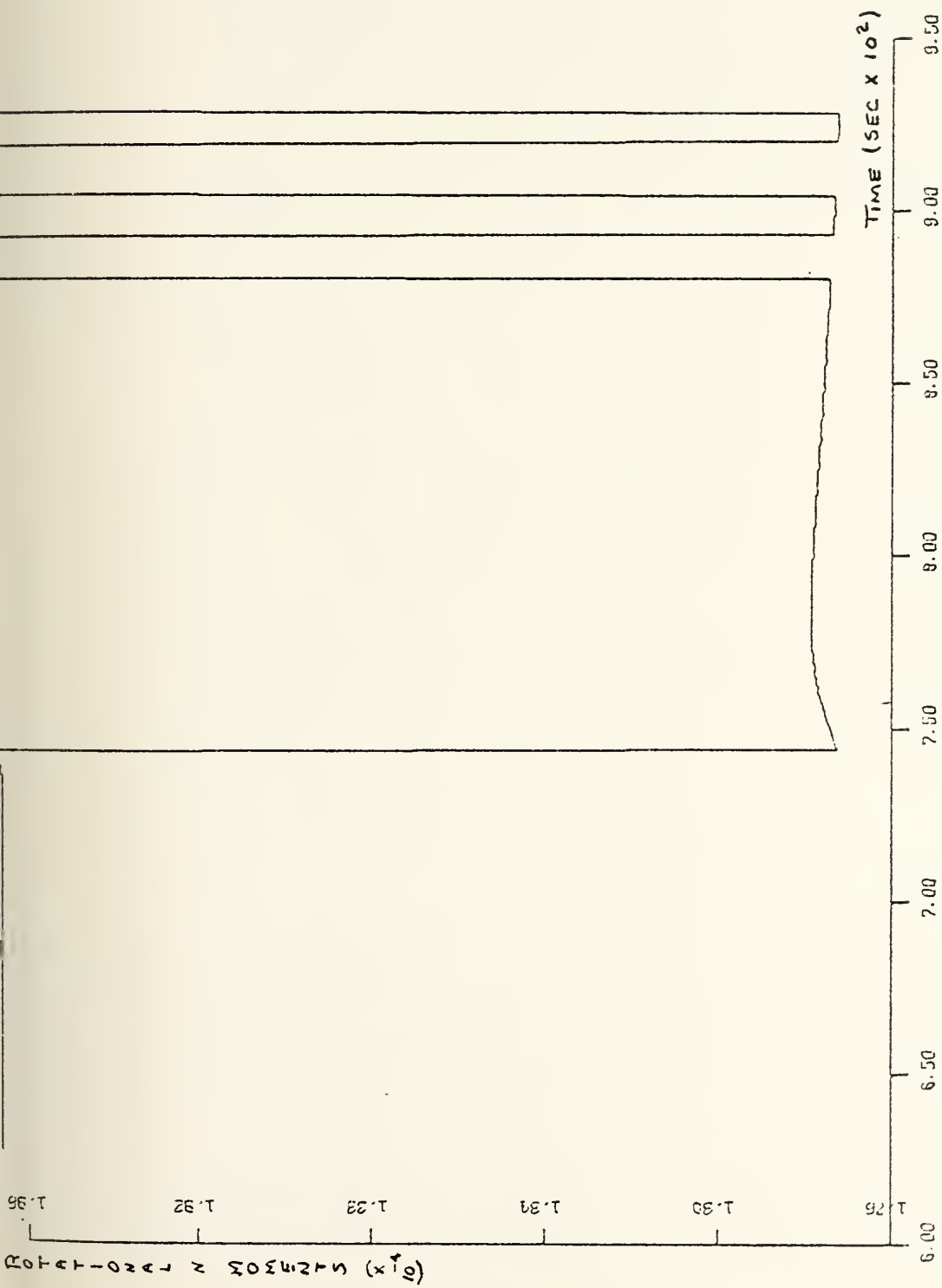


Figure III-31  
Turn Phase N Moments

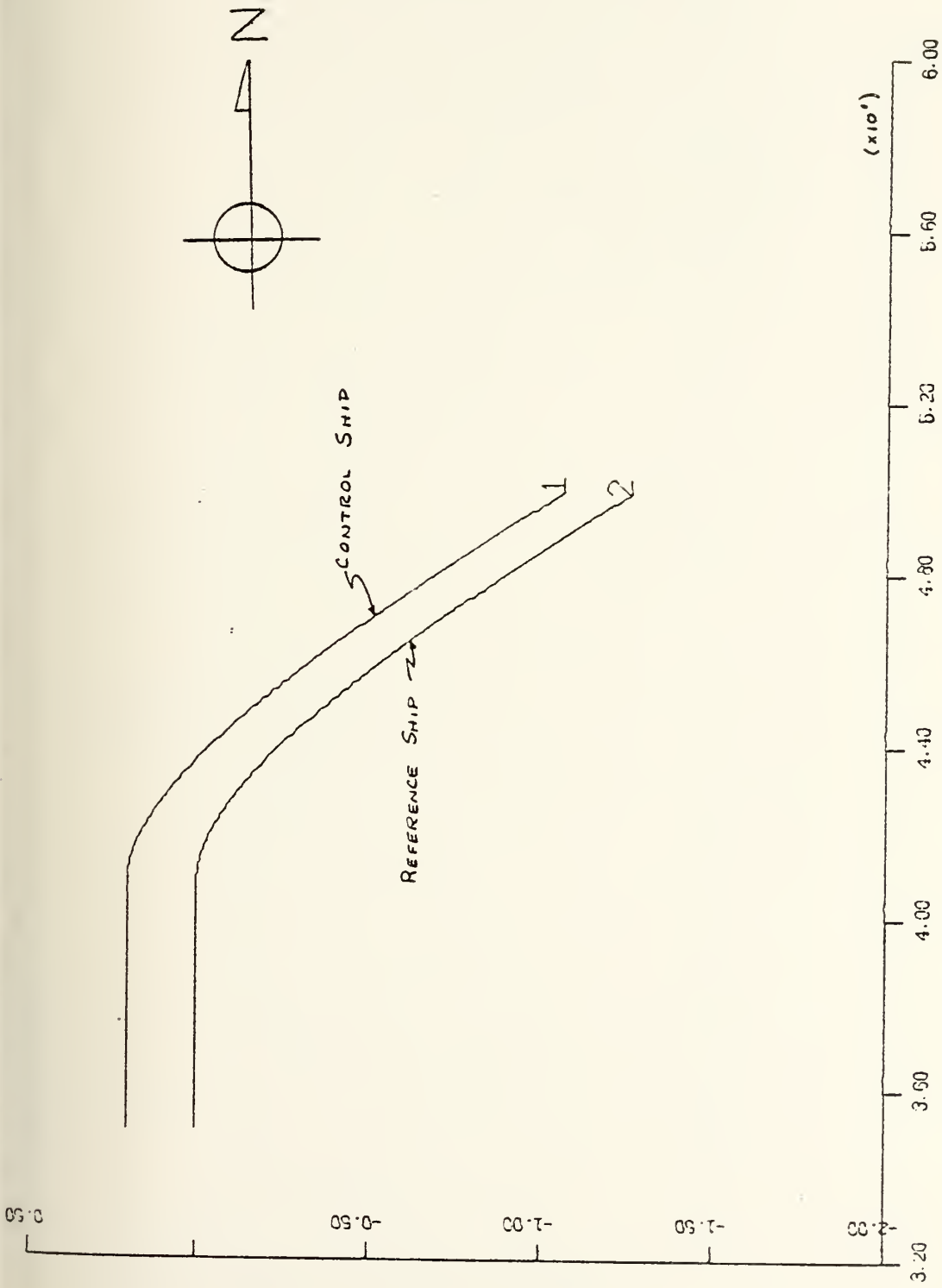


Figure III-32  
Turn Phase Geographic Plot

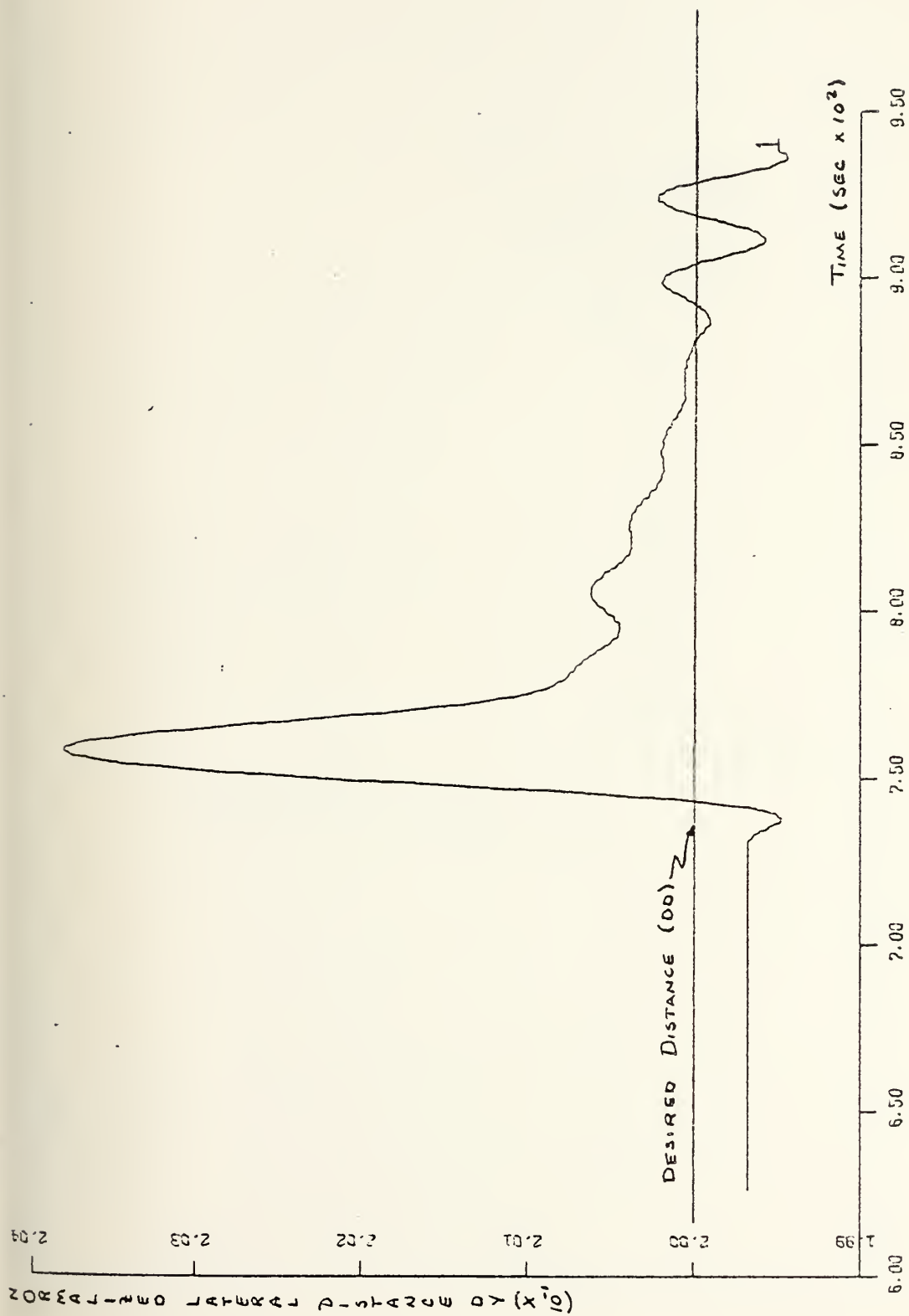


Figure III-33  
Turn Phase Lateral Distance DY

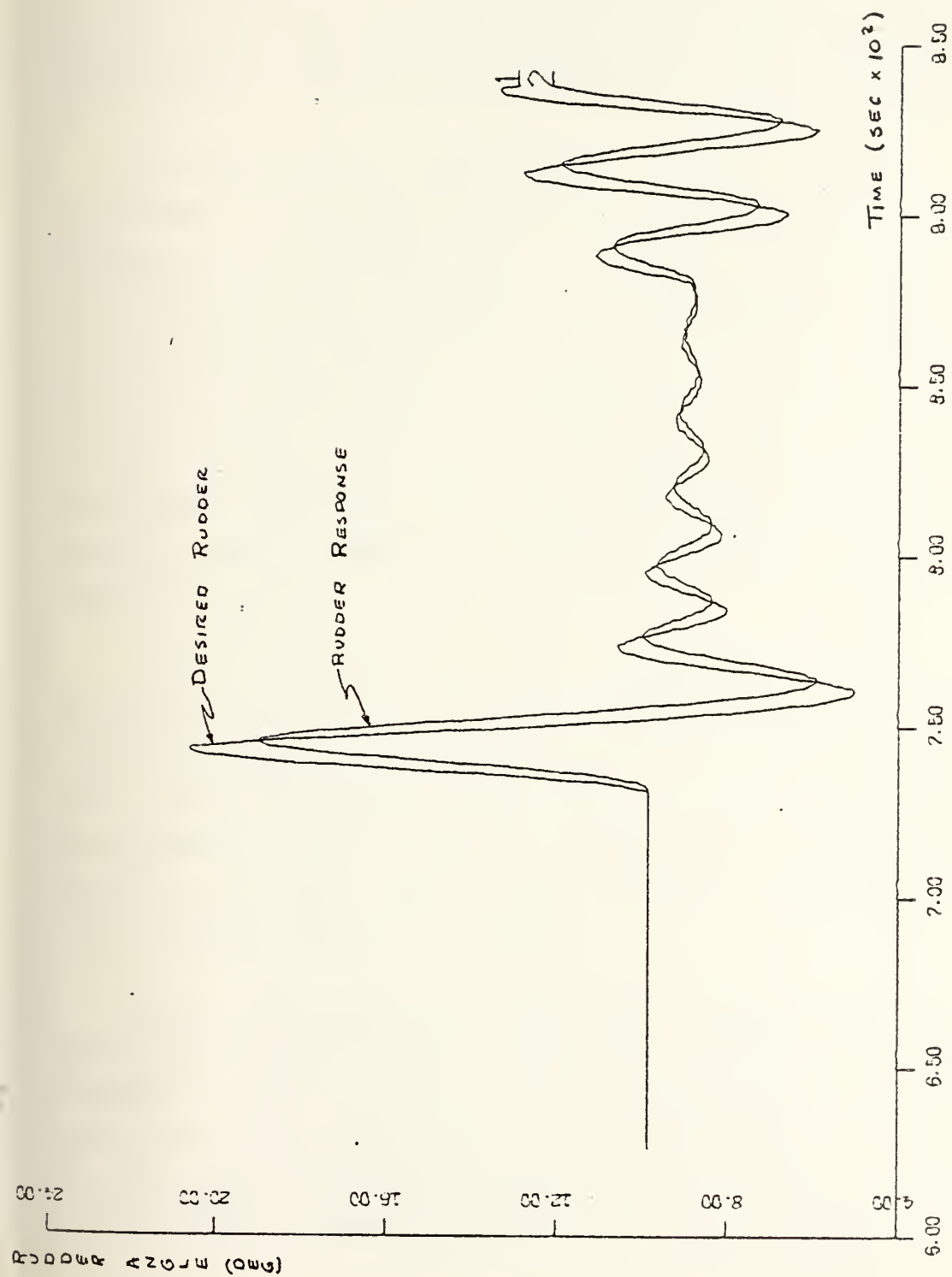


Figure III-34  
Turn Phase Rudder Response

#### g. Varying Initial Conditions

The results obtained in the previous section are most gratifying but actually incomplete. This system must work for other initial conditions quite different from those envisioned in the optimization scenario. The initial approach can realistically commence at points other than 5 ship lengths astern and displaced by 0.4 ship lengths.

By simulating this system with varying initial positions, the relative efficiency and worth of the control system can be observed. This was done in successive test runs whose initial conditions and corresponding plot figures are tabulated in table III-3. For the sake of brevity only those figures required to illustrate the relative efficiency of the control system are included. The corresponding initial optimization simulation figures are listed for cross reference. The turn phase plots for all runs except 4 and 6 exactly match that of the initial simulation and are not repeated here.

Runs 3, 5 and 6 were accomplished to show that no ambiguities exist in the control scheme to prohibit adequate real life initial conditions. Run 3 simulates the situation most often encountered by this author in the RAS environment. This scenario starts the control ship dead astern at 5.0 ship lengths and brings it alongside at 0.2 ship lengths lateral separation.

Run 5 is a situation where the approaching ship is purposely placed out of position on the wrong side for approach. The control scheme adequately corrects the placement error and will do so for all cases of this type, provided that there is adequate maneuvering room astern of the reference vessel (in this case 2.6 ship lengths was

	RUN	Initial Development	1	2	3	4	5	6
Initial Condition	X01	5.0	4.0	3.0	5.0	5.0	5.0	5.0
	Y02	0.4	0.3	0.25	0.0	0.2	-0.4	-0.4
	DD	0.2	0.2	0.2	0.2	0.15	0.2	0.2
Desired Distance								
Approach Side	IS	STBD	STBD	STBD	STBD	STBD	STBD	PORT
Approach Phase Figures (III-)								
YAW		23	35	38	41	44	47	50
Geographic Plot		26	36	39	42	45	48	51
Rudder Response		28	37	40	43	46	49	52
Turn Phase Figures (III-)								
YAW			29			53	29	56
Geographic Plot			32			54	32	57
Rudder Response			34			55	34	58

Table III-3  
Initial Condition Simulation Cross Reference

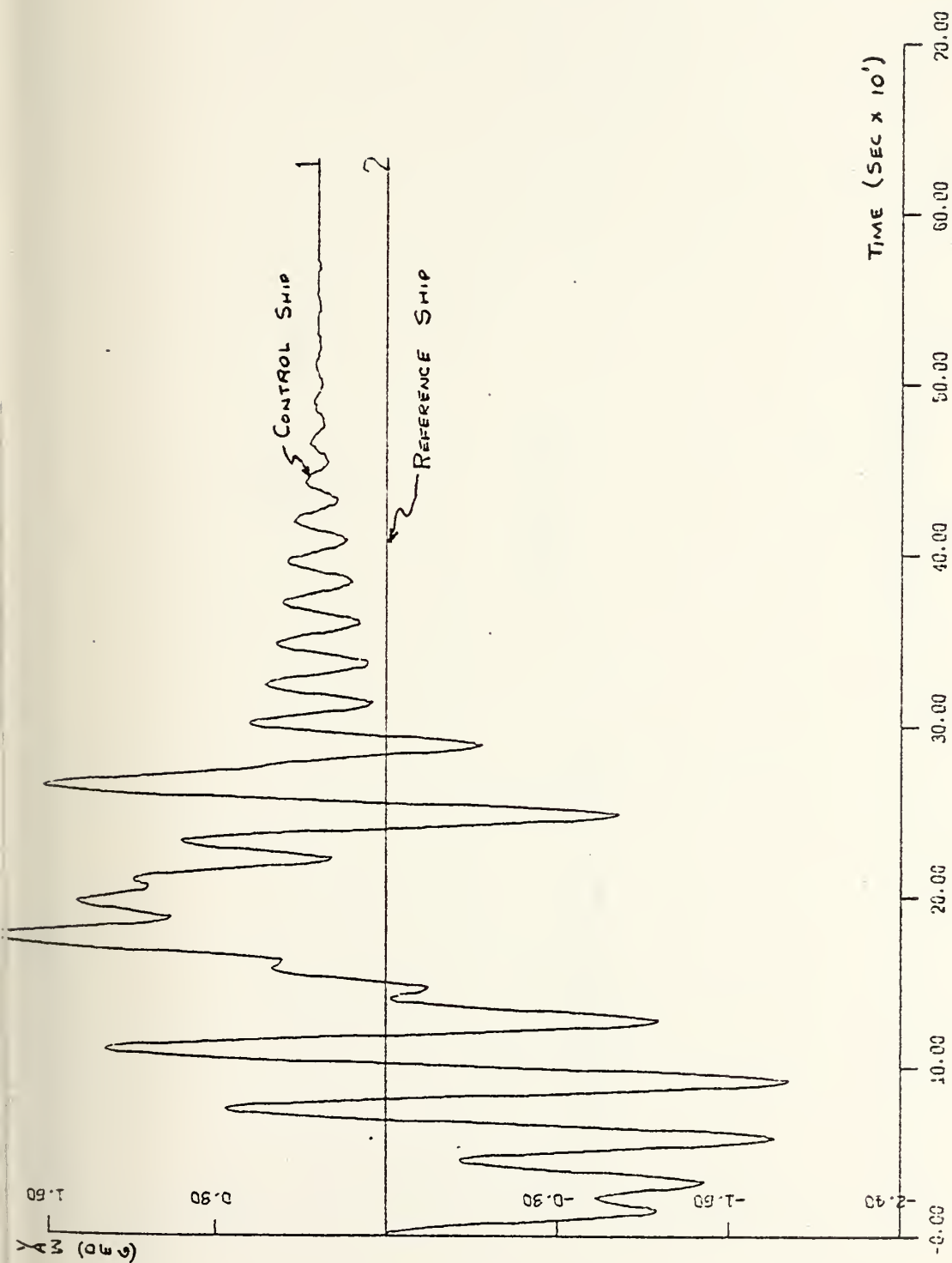


Figure III-35  
Approach Phase Run #1 Yaw Response

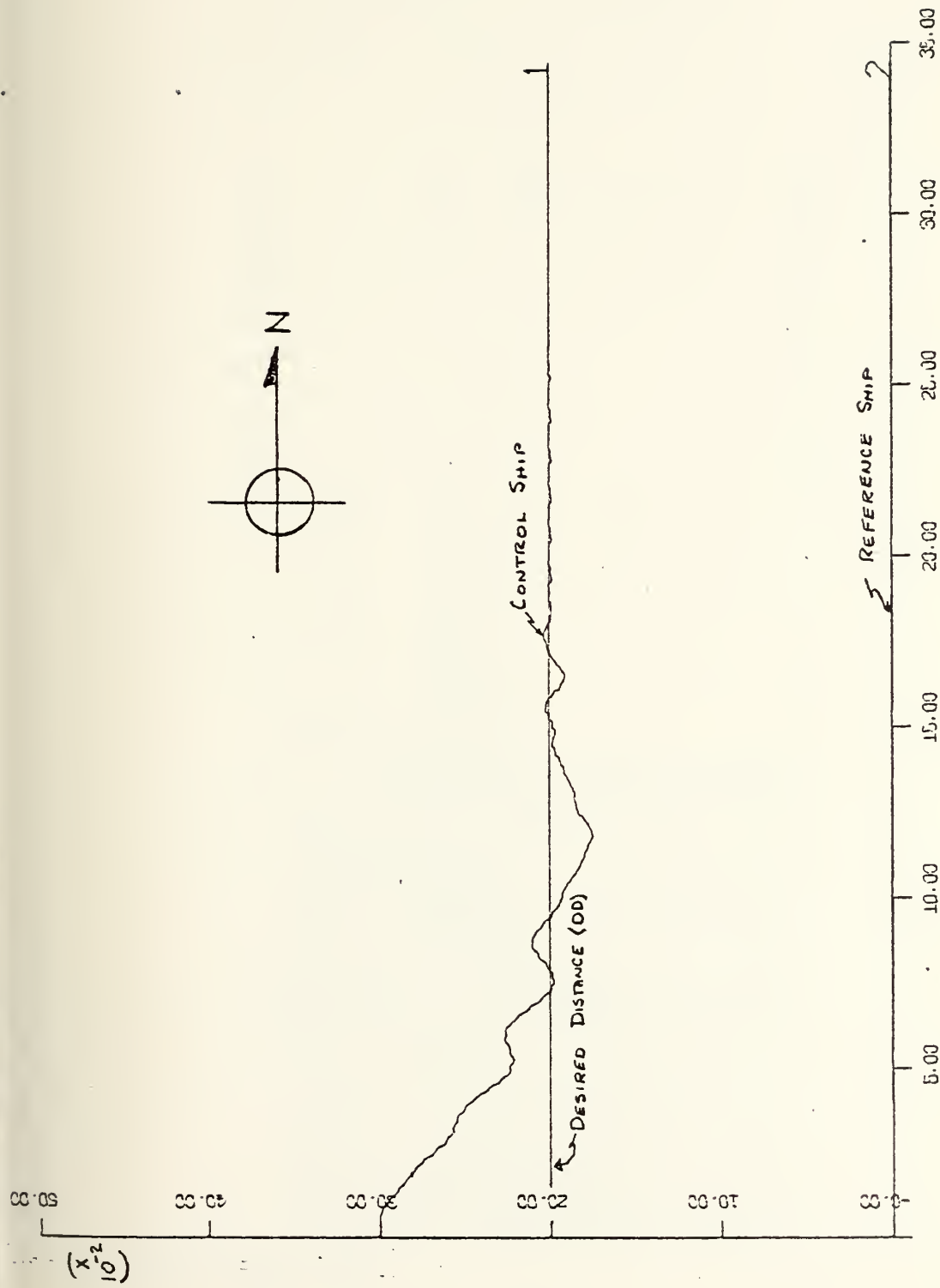


Figure III-36  
Approach Phase Run #1 Geographic Plot

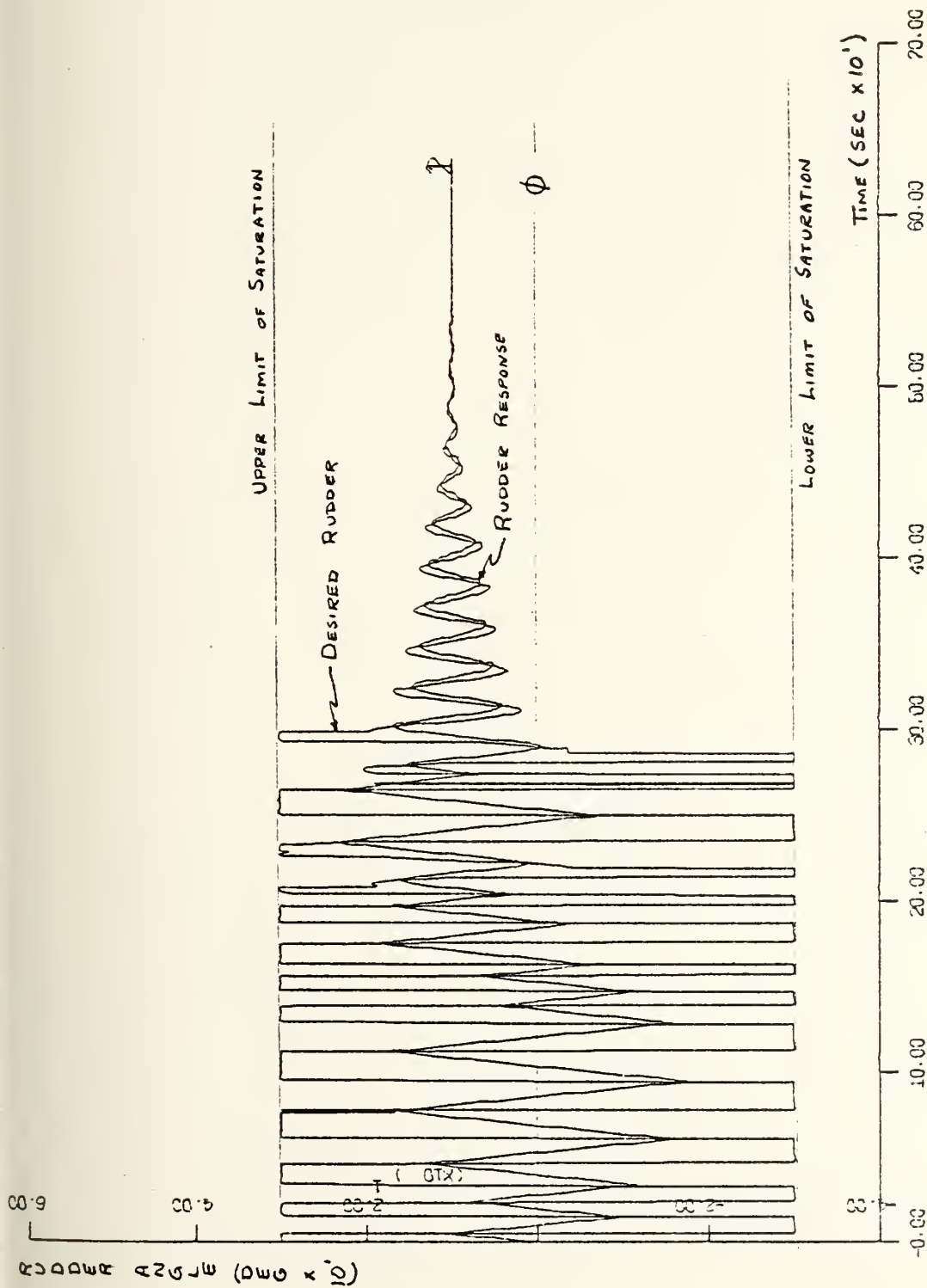


Figure III-37  
Approach Phase Run #1 Rudder Response

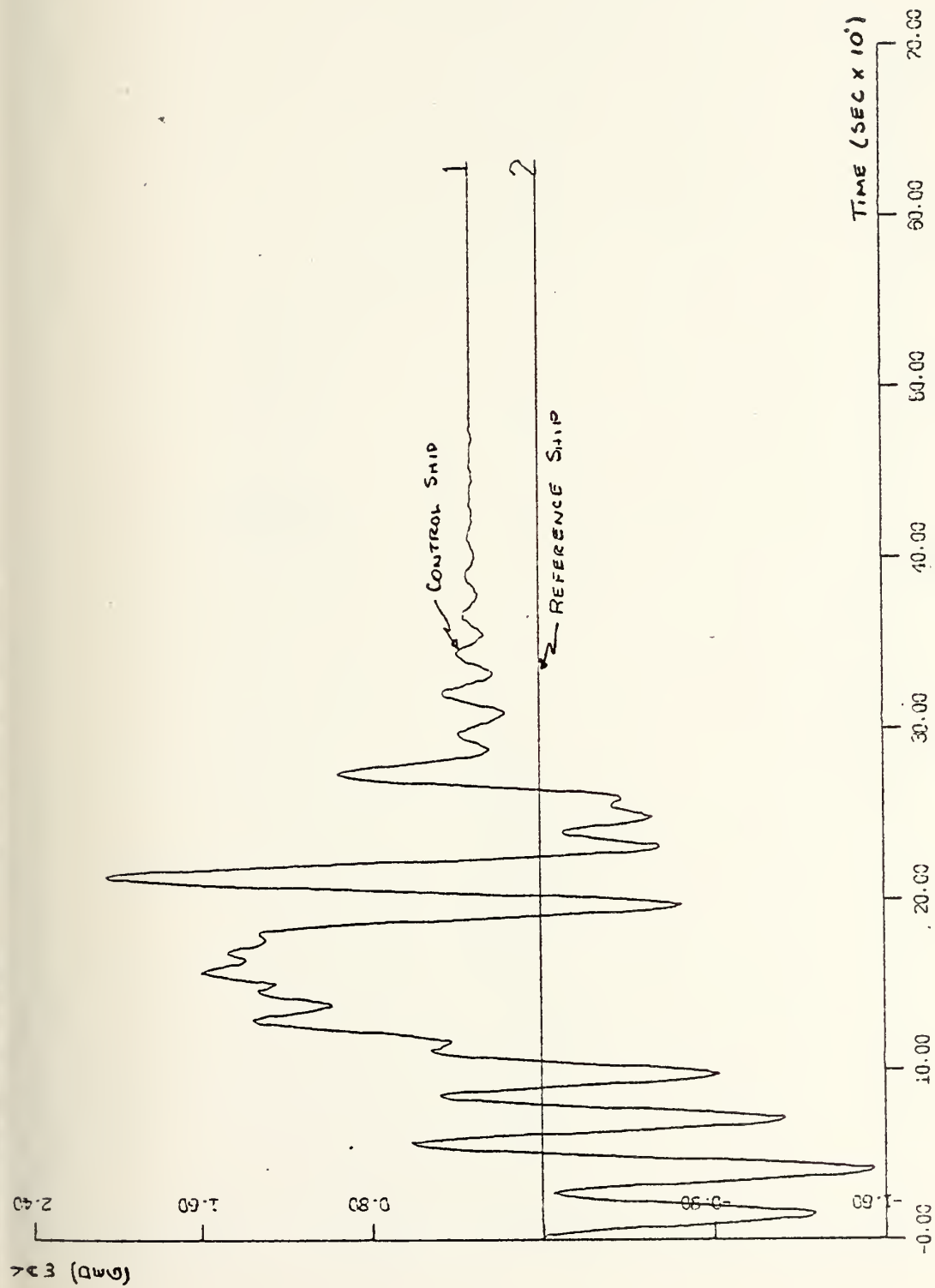


Figure III-38

Approach Phase Run #2 Yaw Response

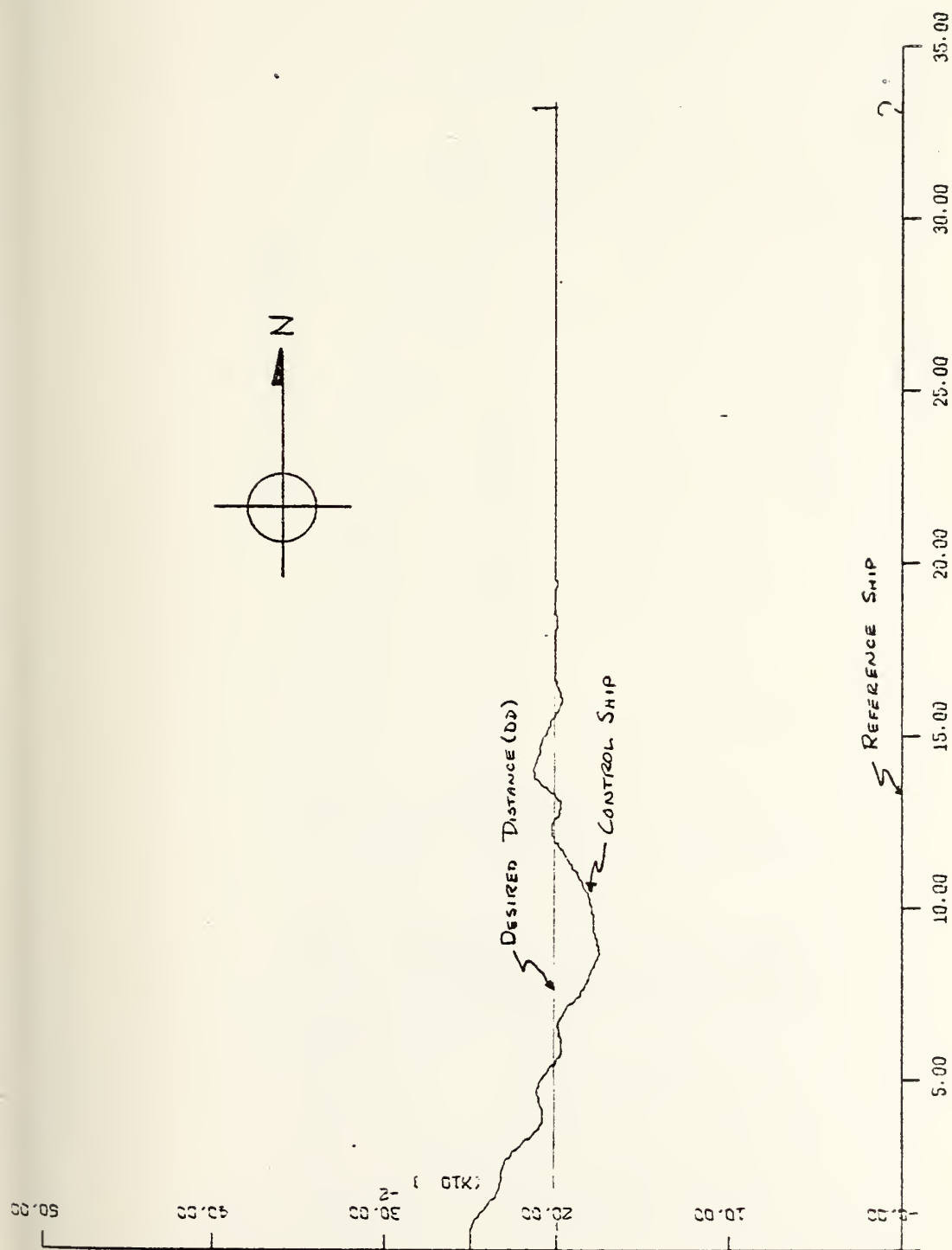


Figure III-39  
Approach Phase Run #2 Geographic Plot

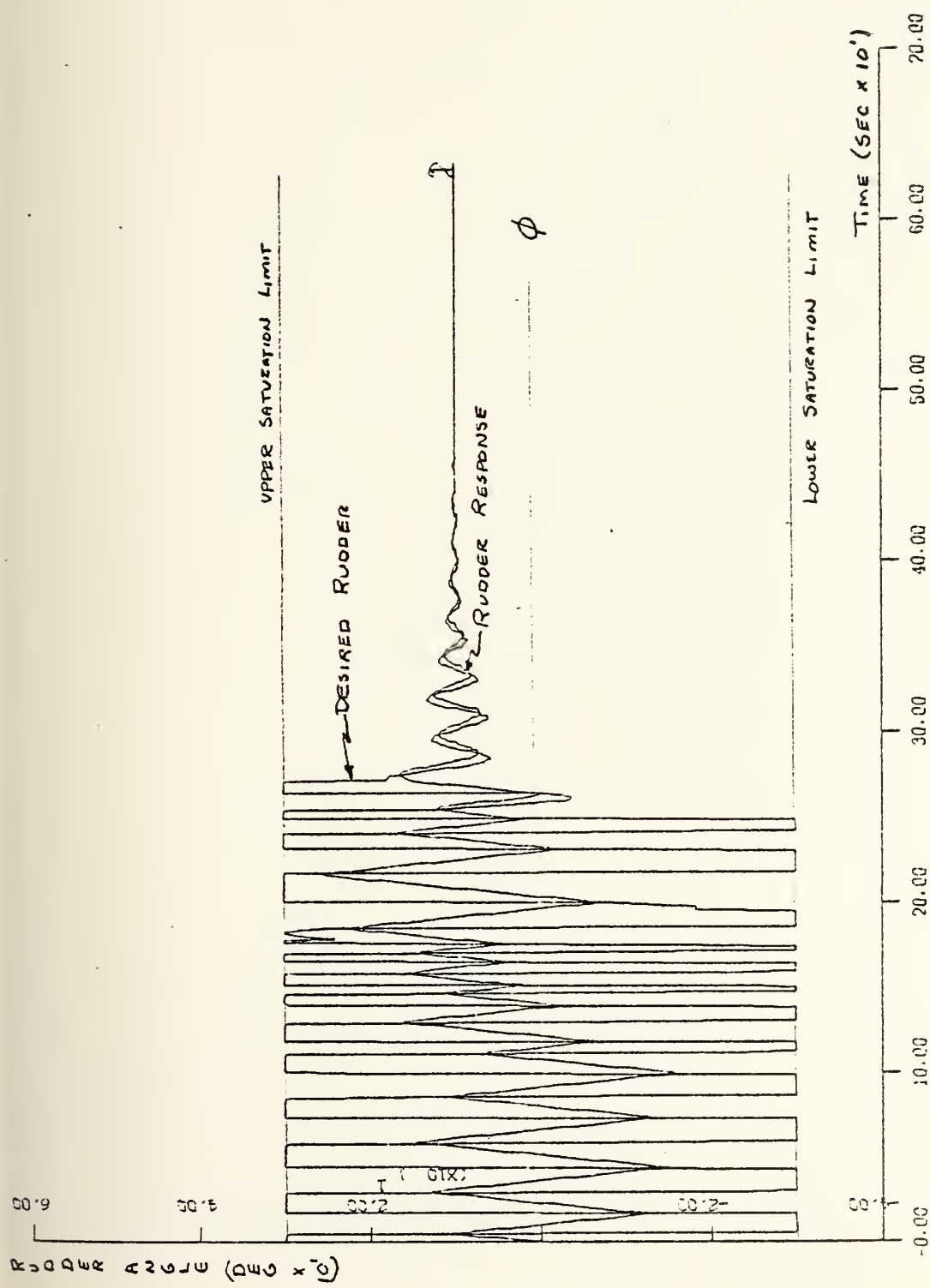


Figure III-40  
Approach Phase Run #2 Rudder Response

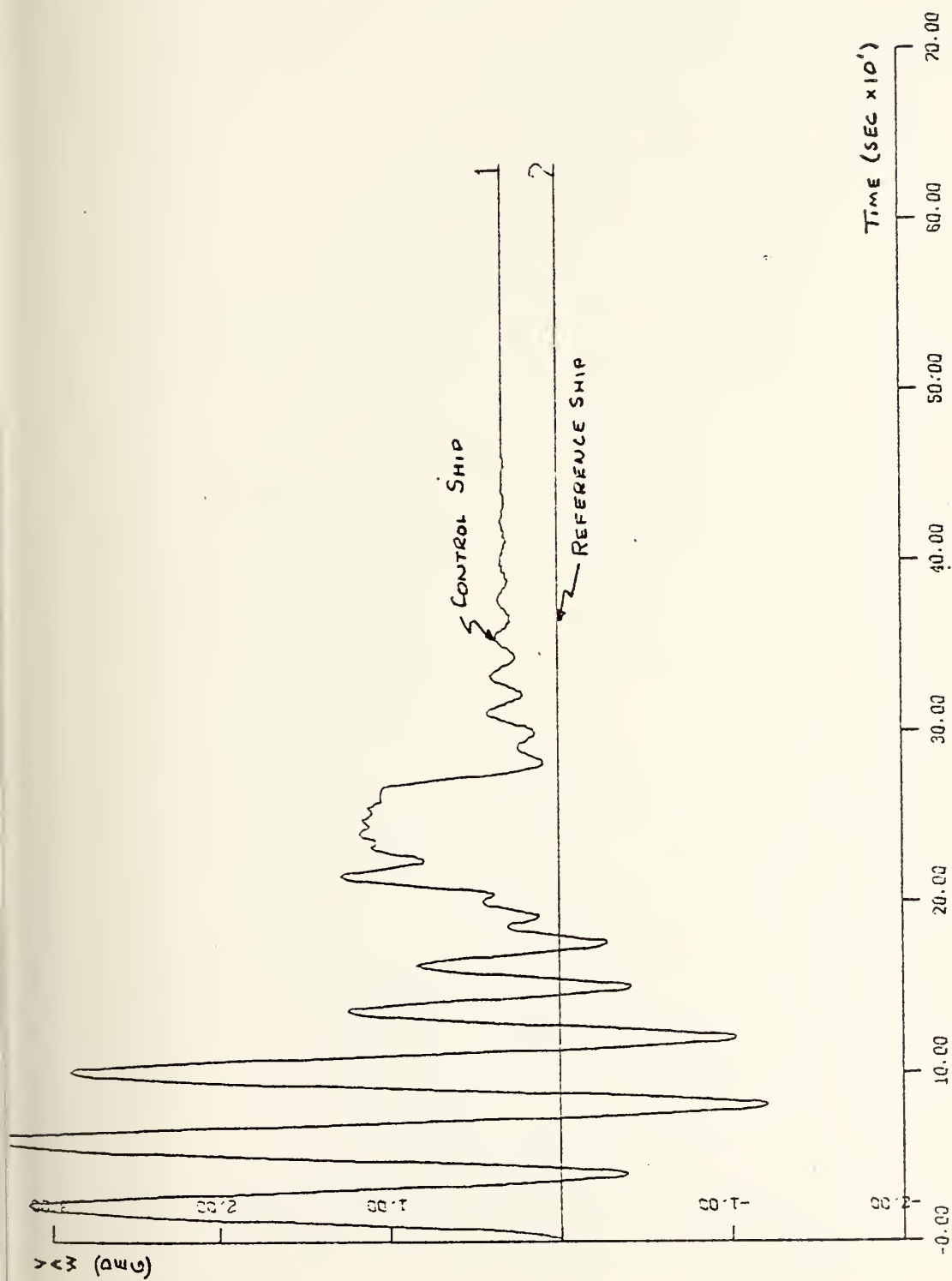


Figure III-41  
Approach Phase Run #3 Yaw Response

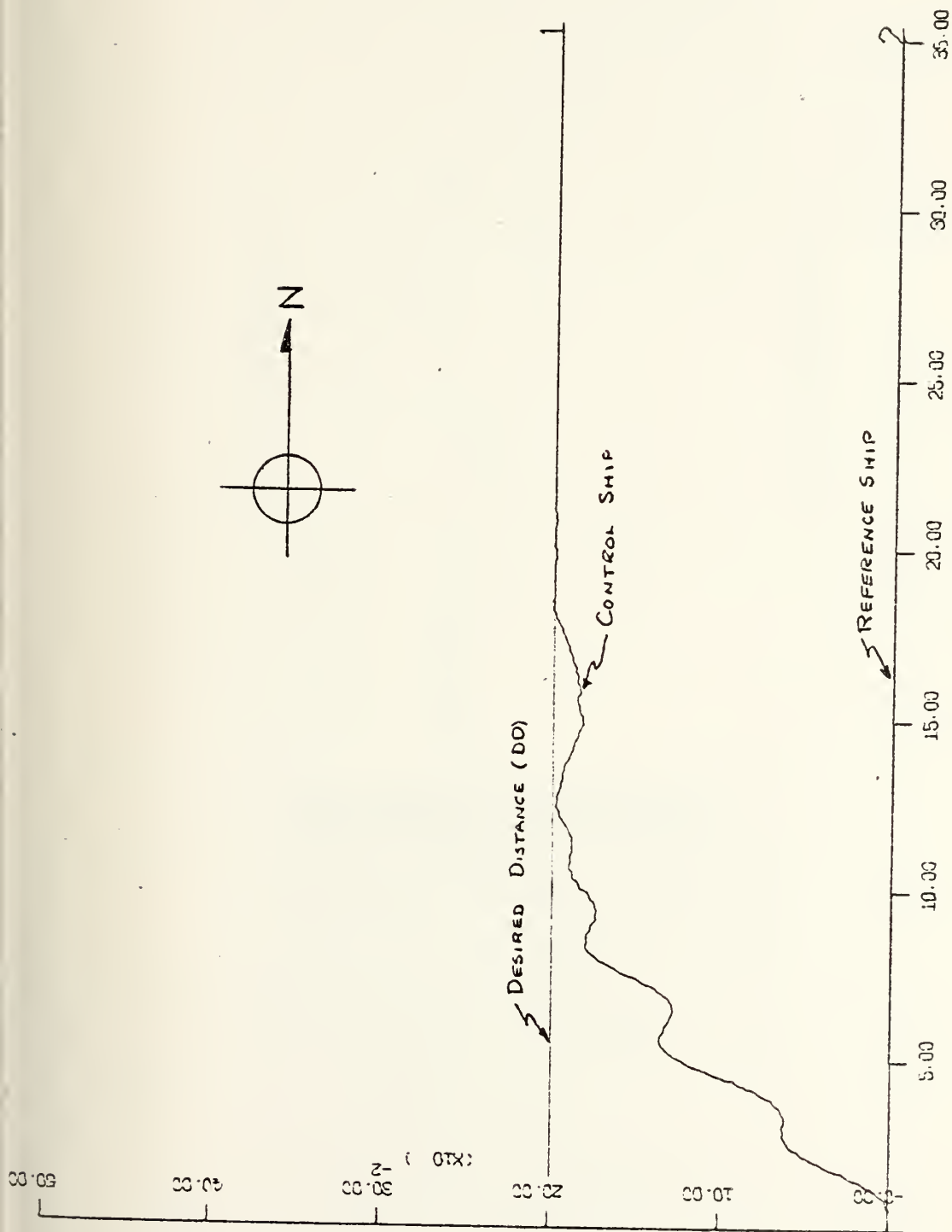


Figure III-42  
Approach Phase Run #3 Geographic Plot

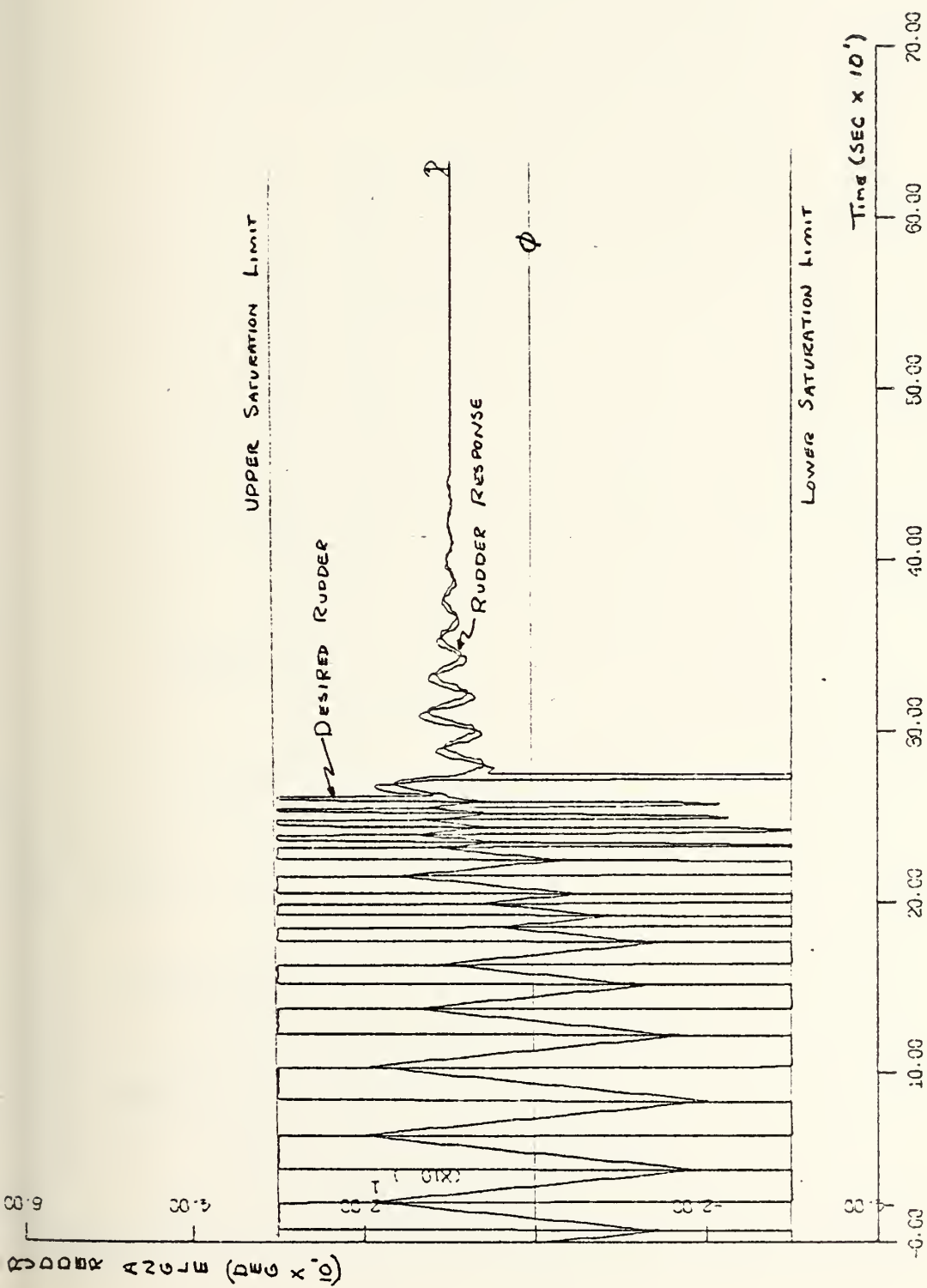


Figure III-43  
Approach Phase Run #3 Rudder Response

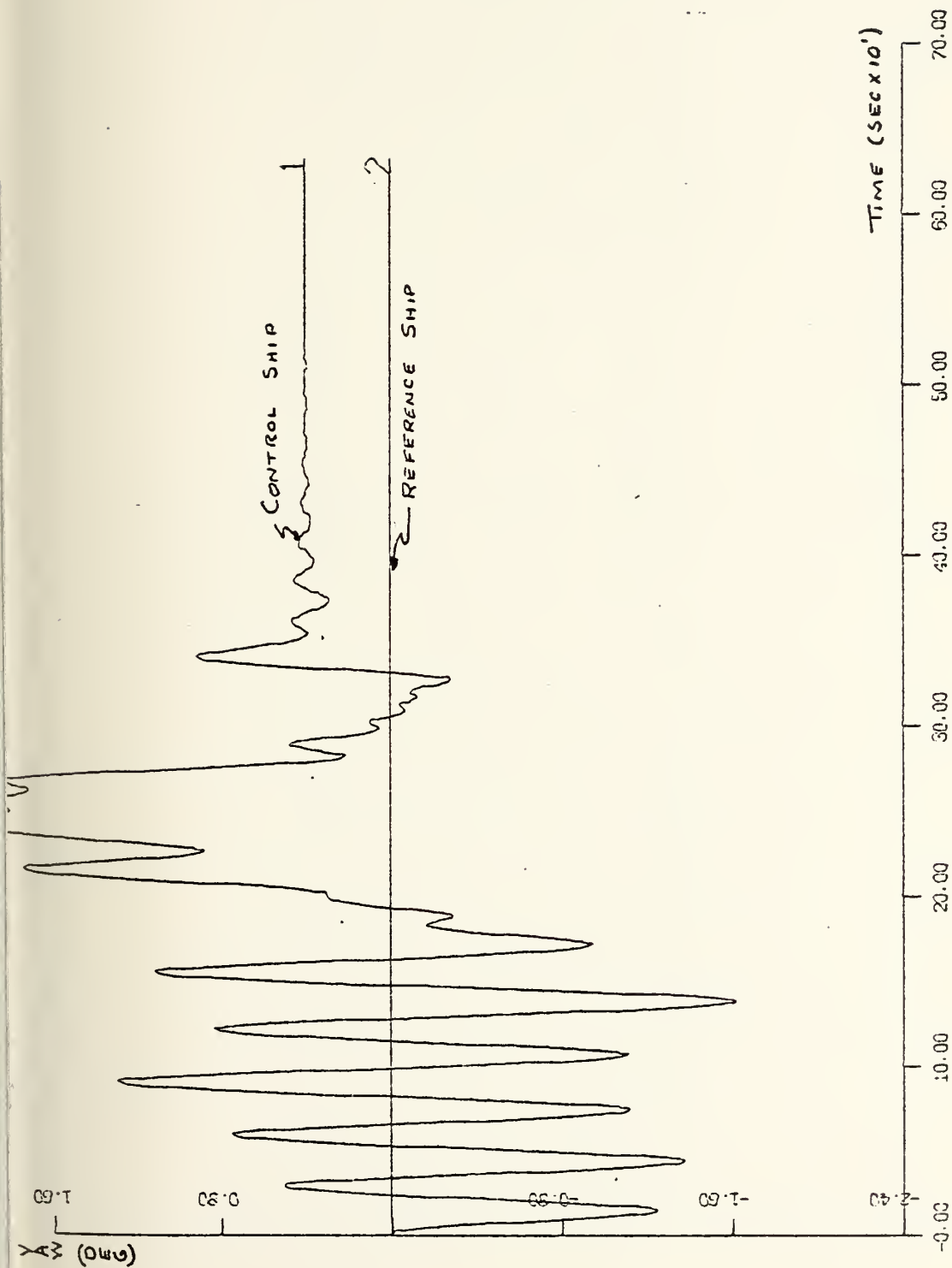


Figure III-44  
Approach Phase Run #4 Yaw Response

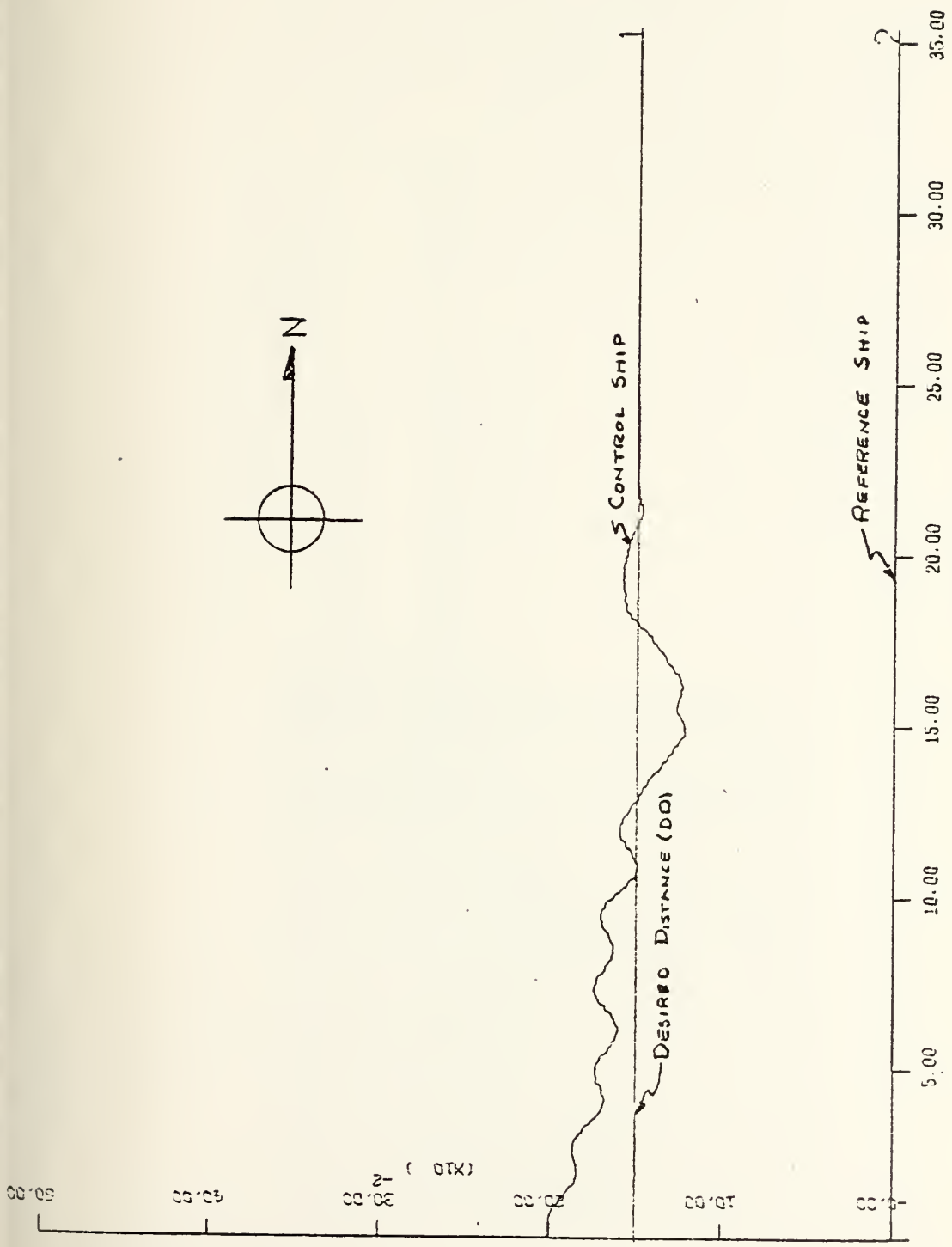


Figure III-45  
Approach Phase Run #4 Geographic Plot

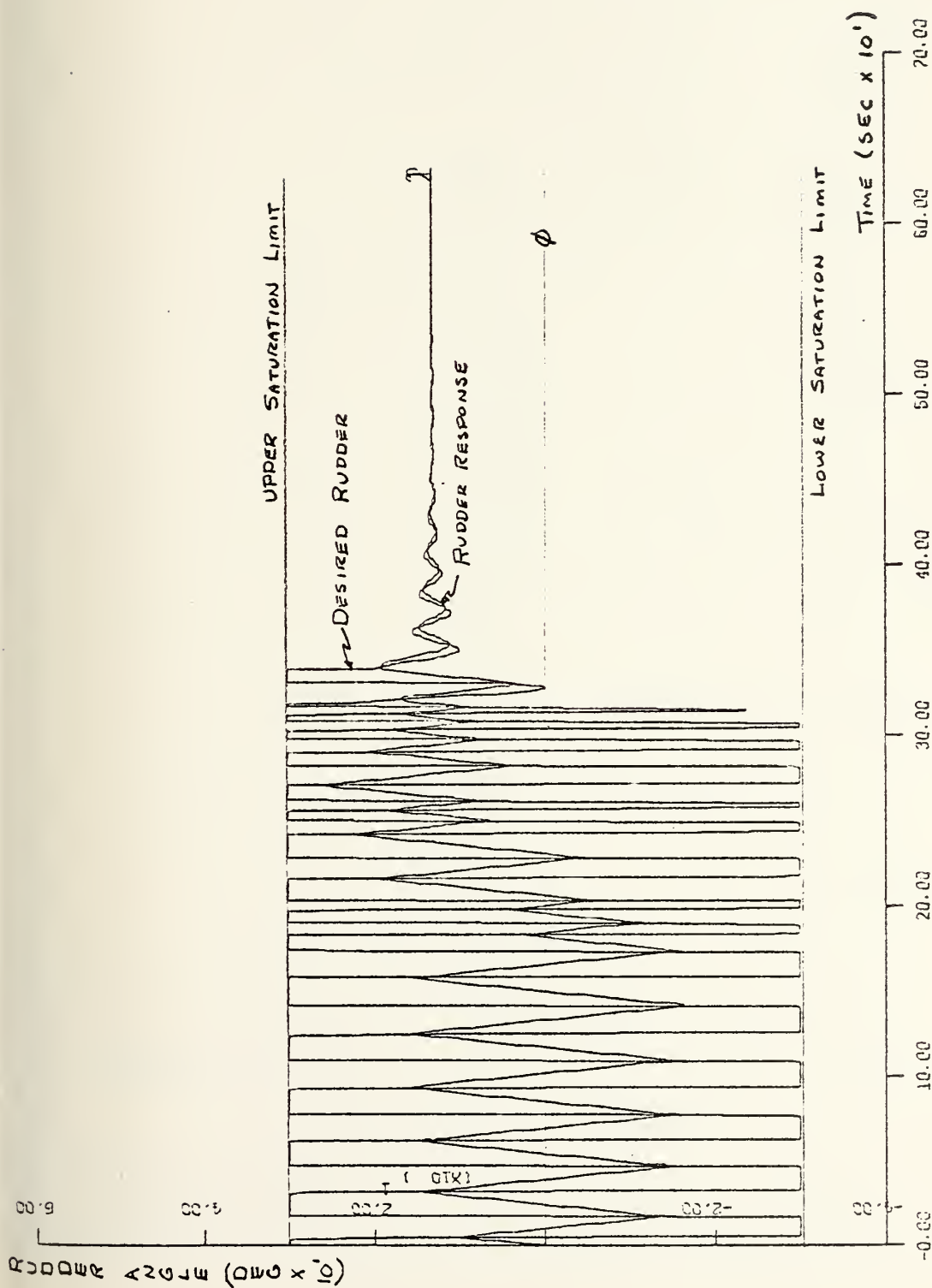


Figure III-46  
Approach Phase Run #4 Rudder Response

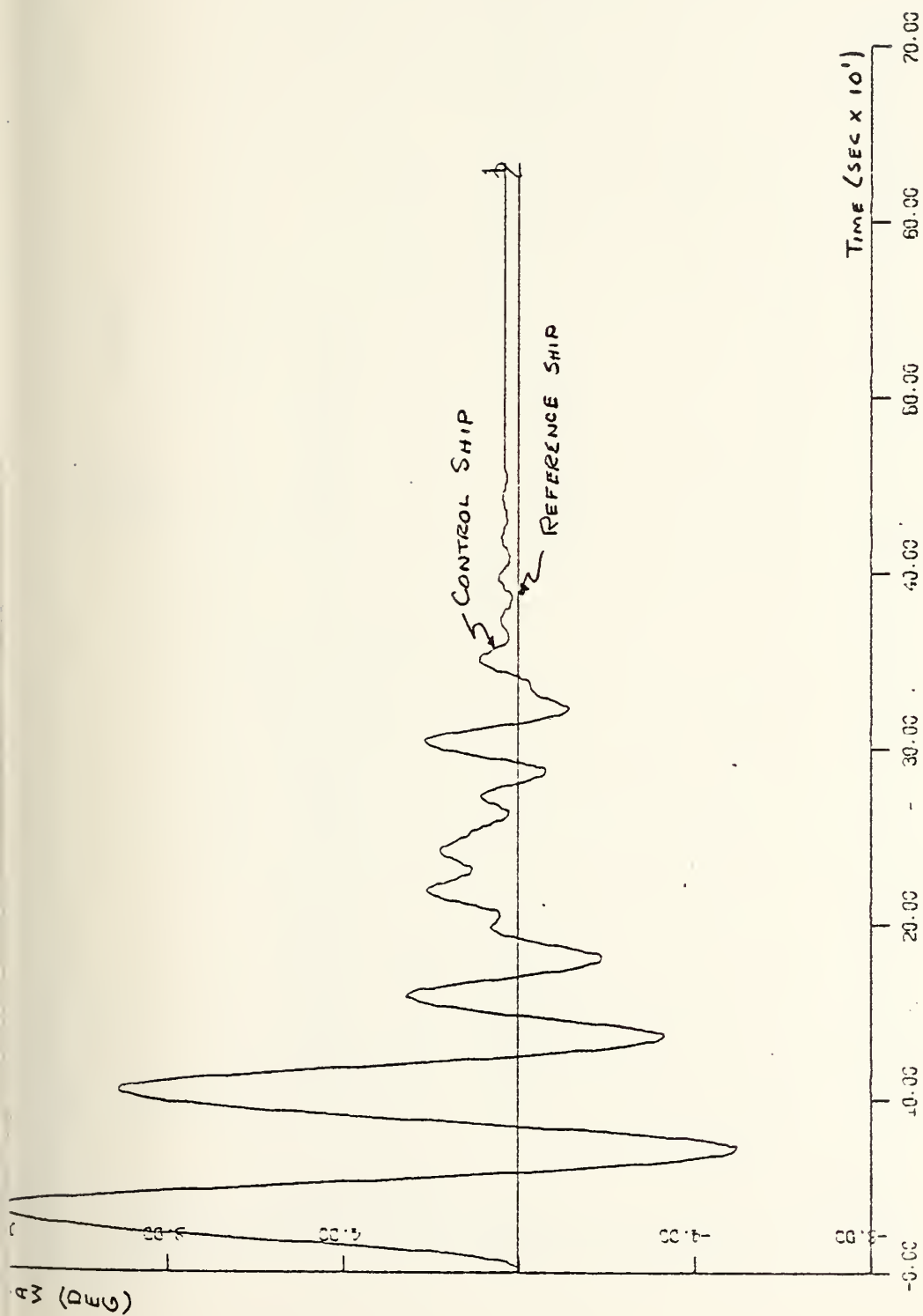


Figure III-47

Approach Phase Run #5 Yaw Response

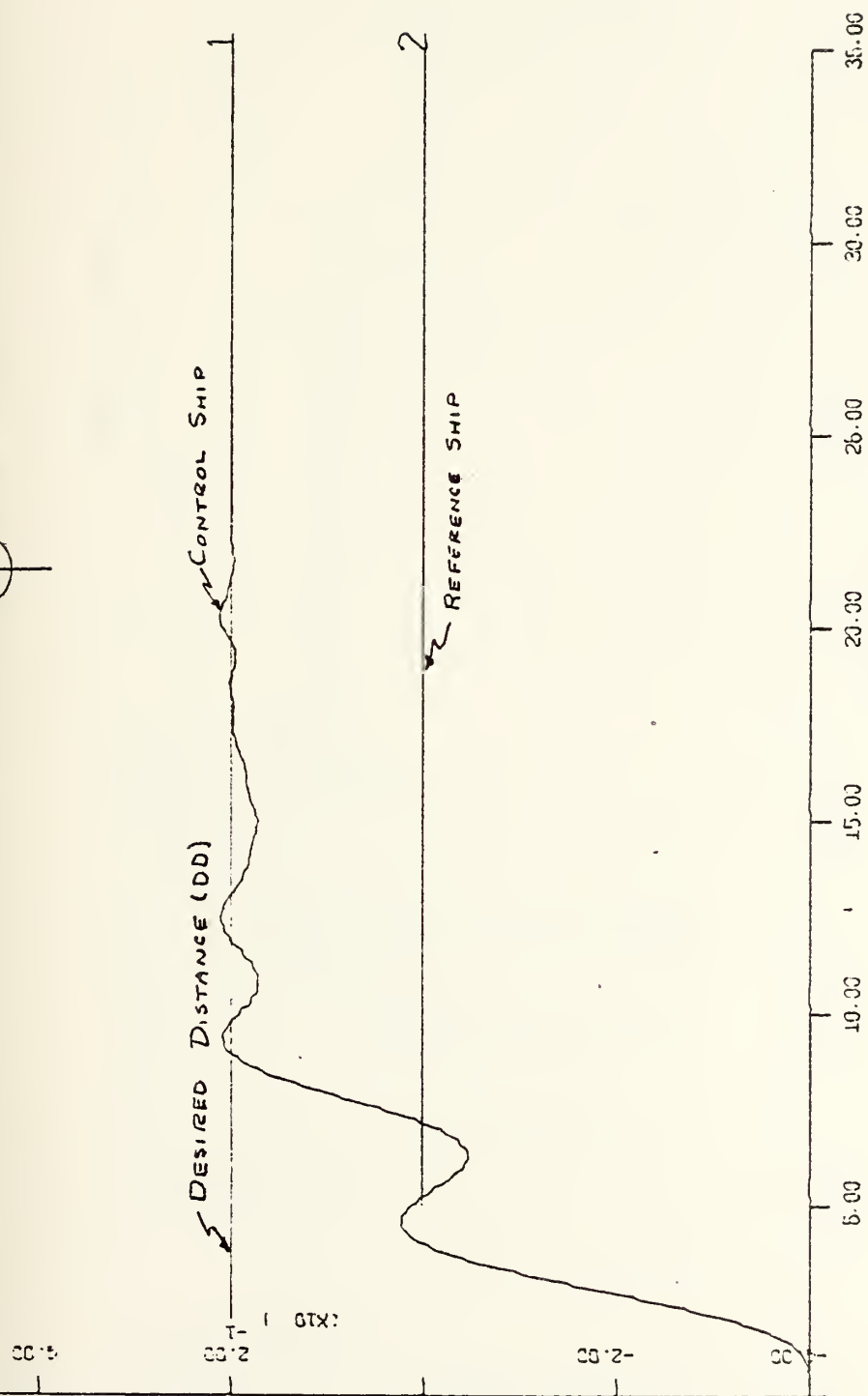


Figure III-48  
Approach Phase Run #5 Geographic Plot

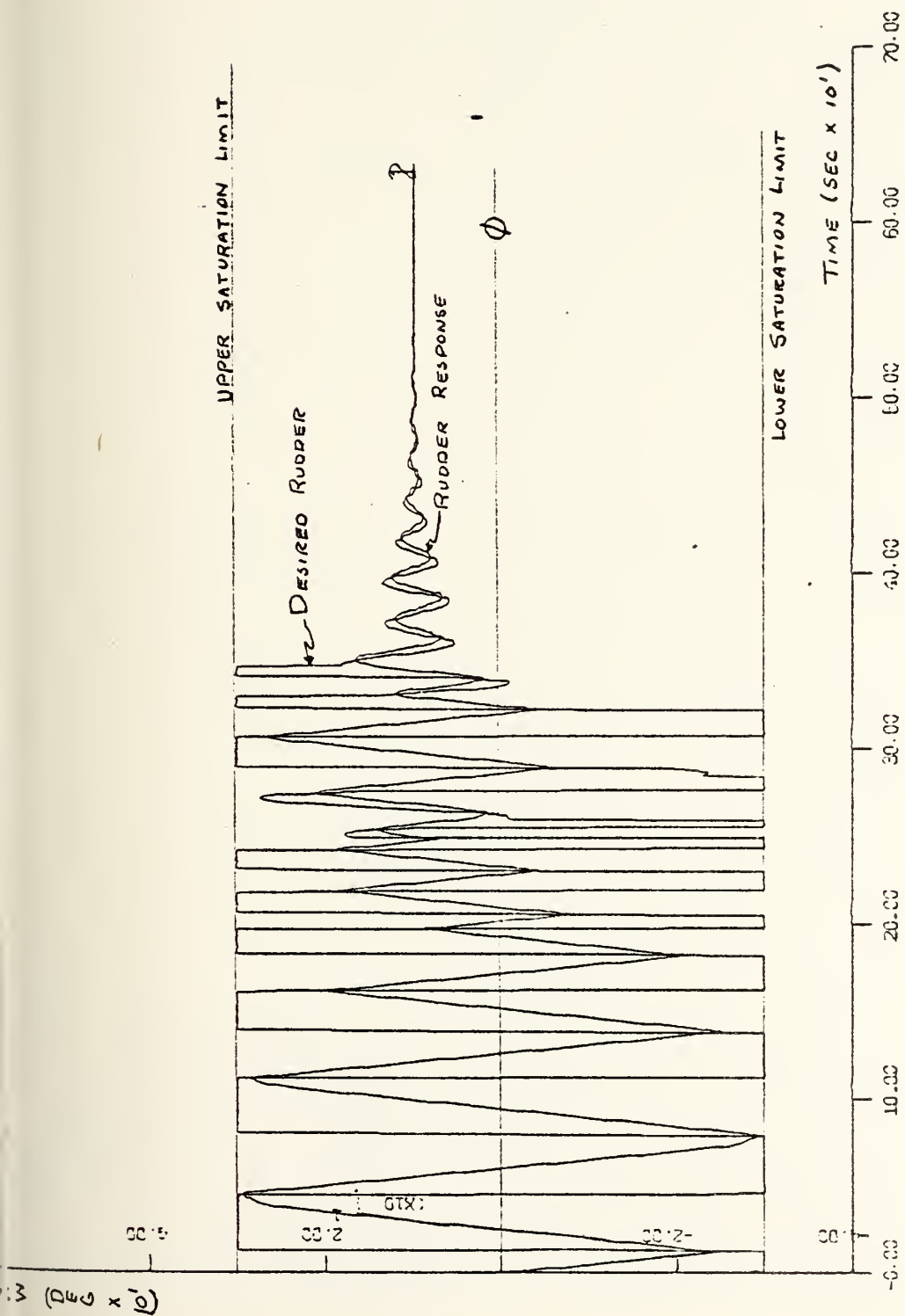


Figure III-49  
Approach Phase Run #5 Rudder Response

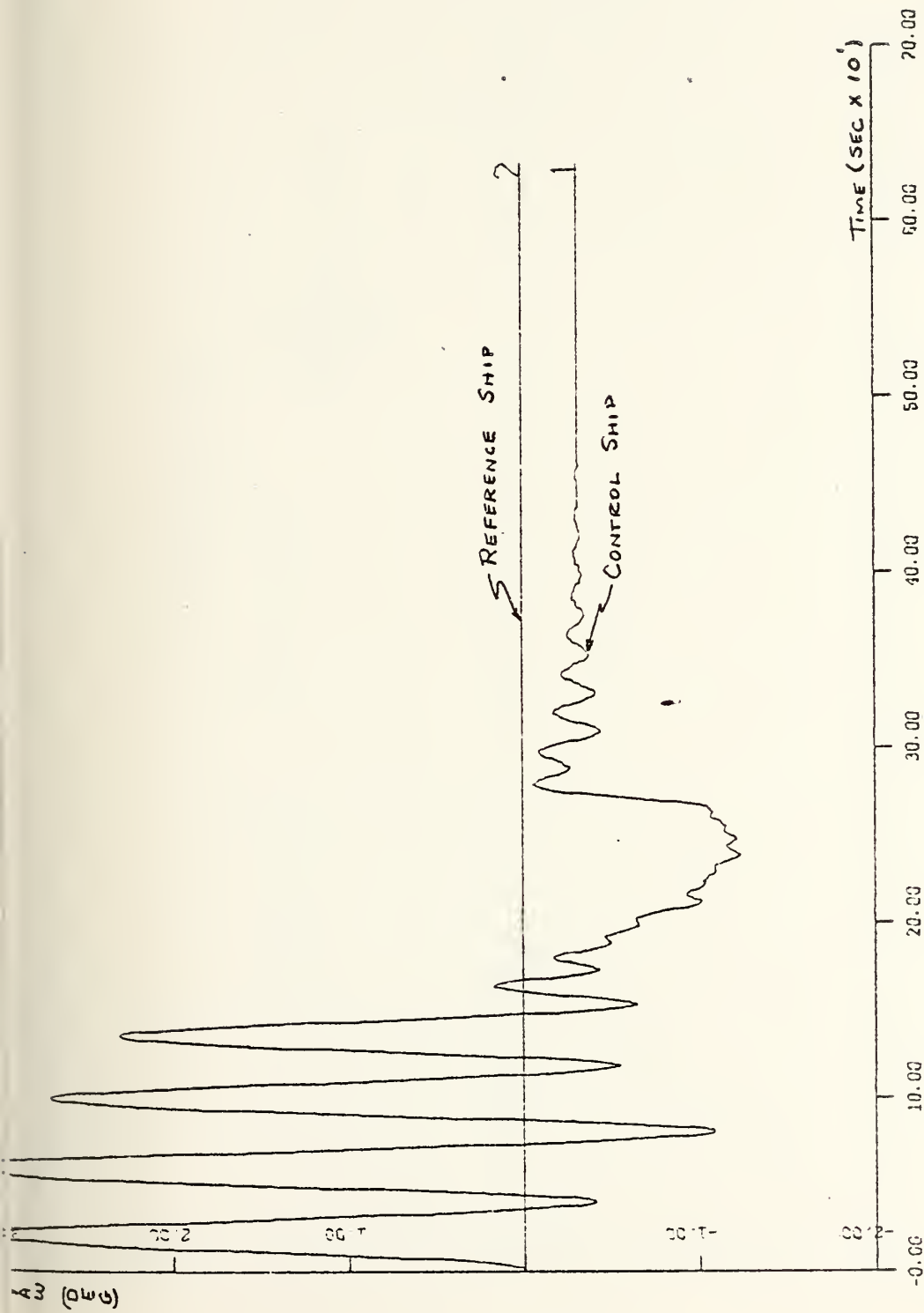


Figure III-50  
Approach Phase Run #6 Yaw Response

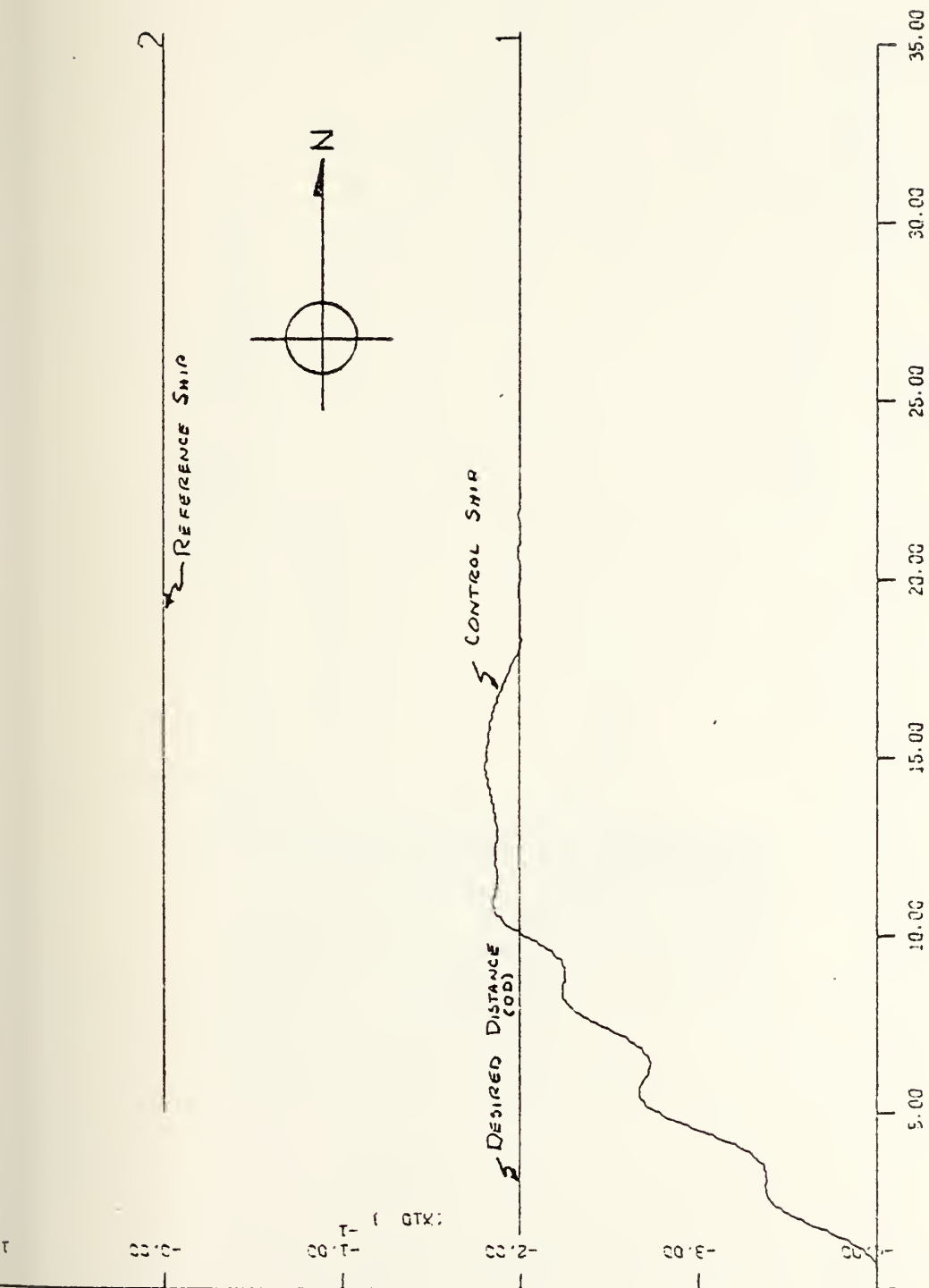


Figure III-51  
Approach Phase Run #6 Geographic Plot

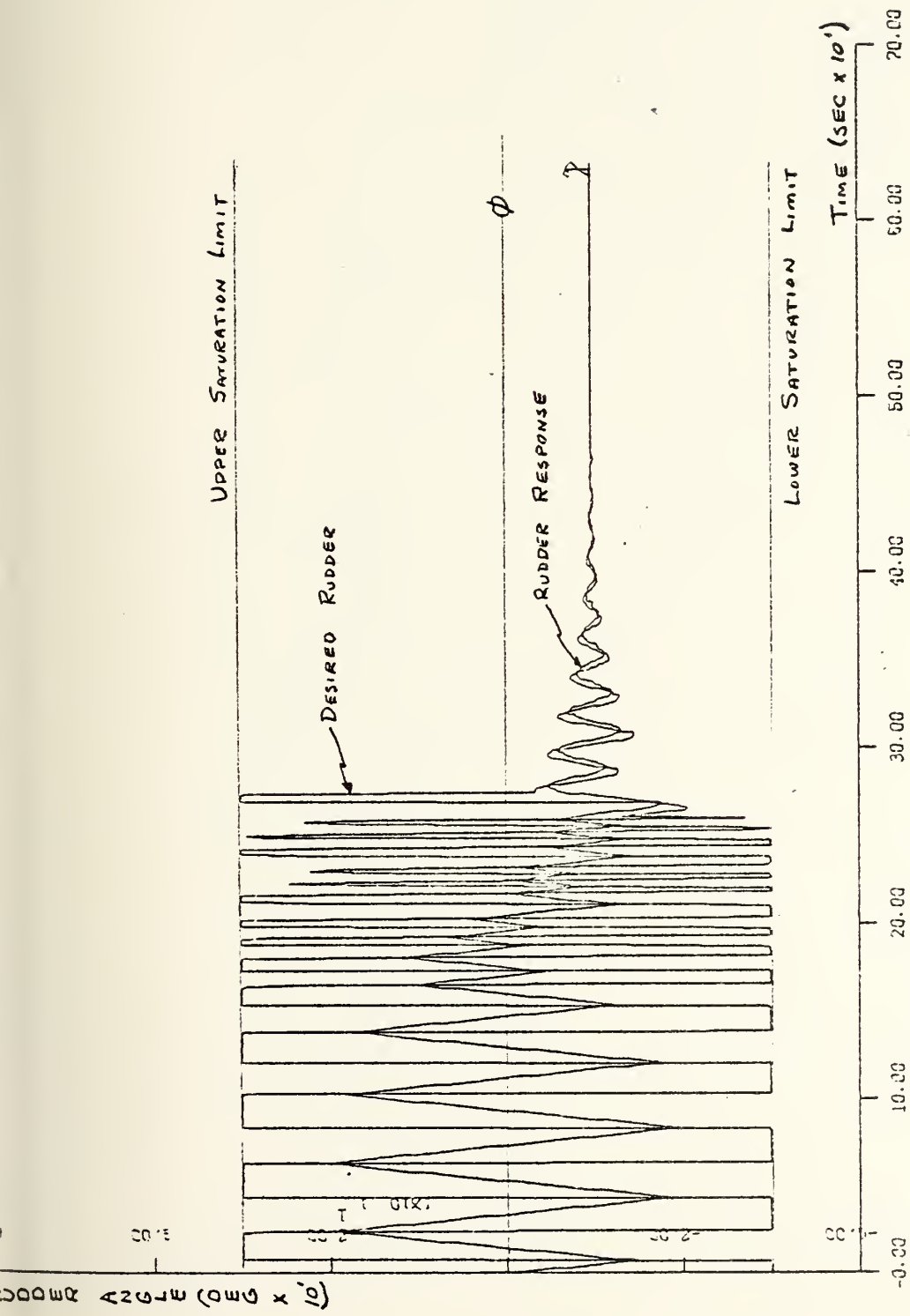


Figure III-52  
Approach Phase Run #6 Rudder Response

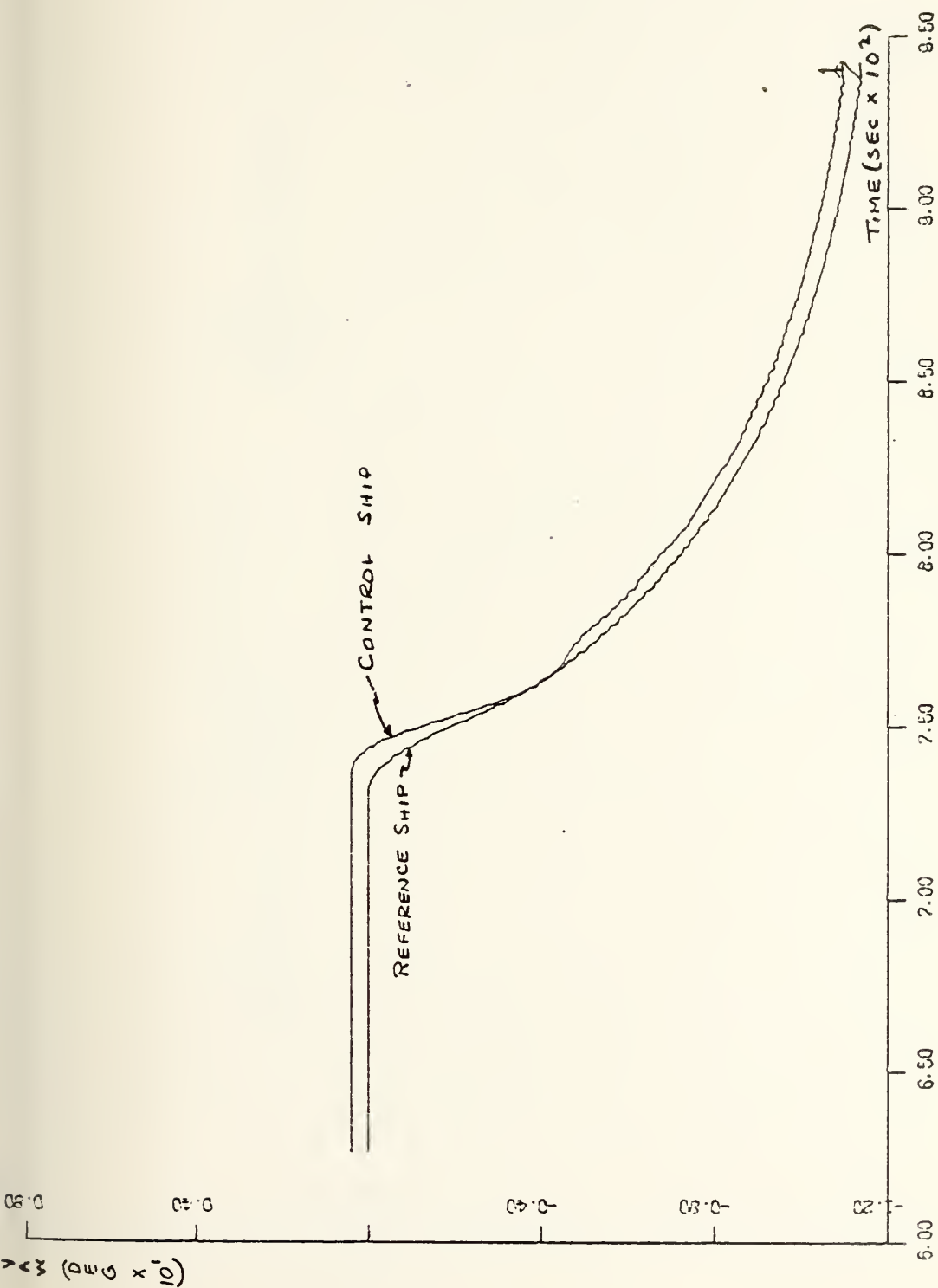


Figure III-53  
Turn Phase Run #4 Yaw Response

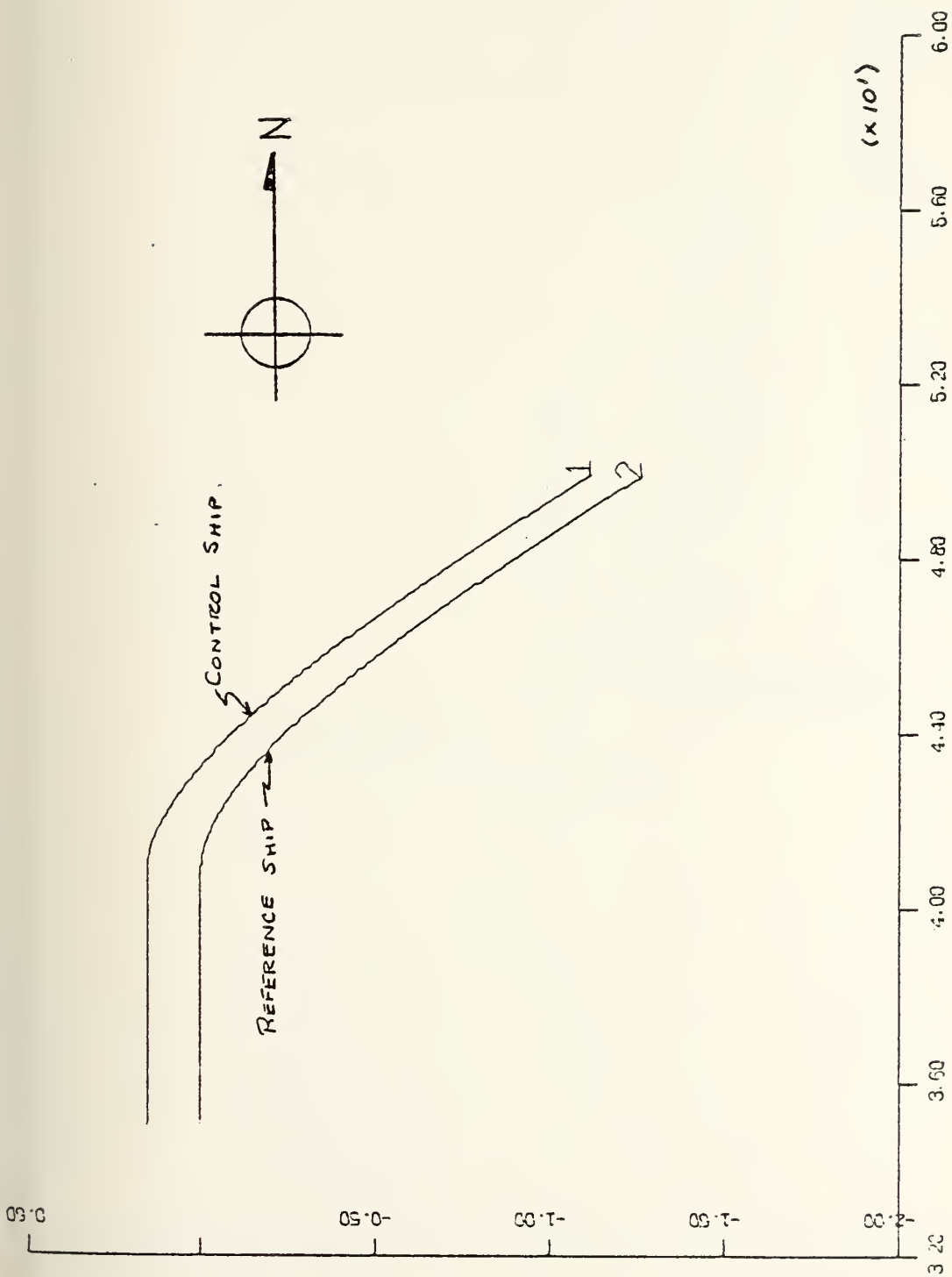


Figure III-54  
Turn Phase Run #4 Geographic Plot

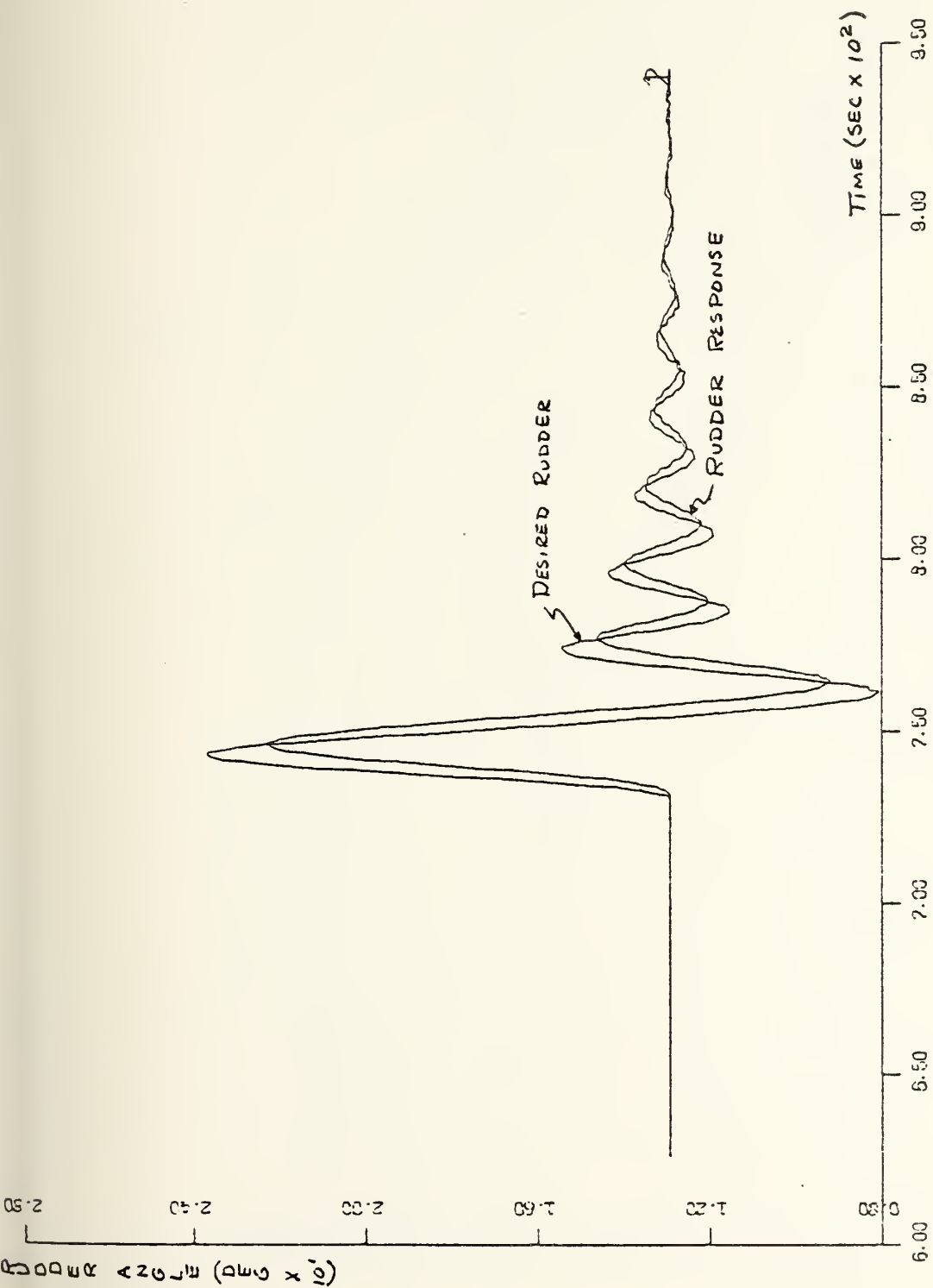


Figure III-55  
Turn Phase Run #4 Rudder Response

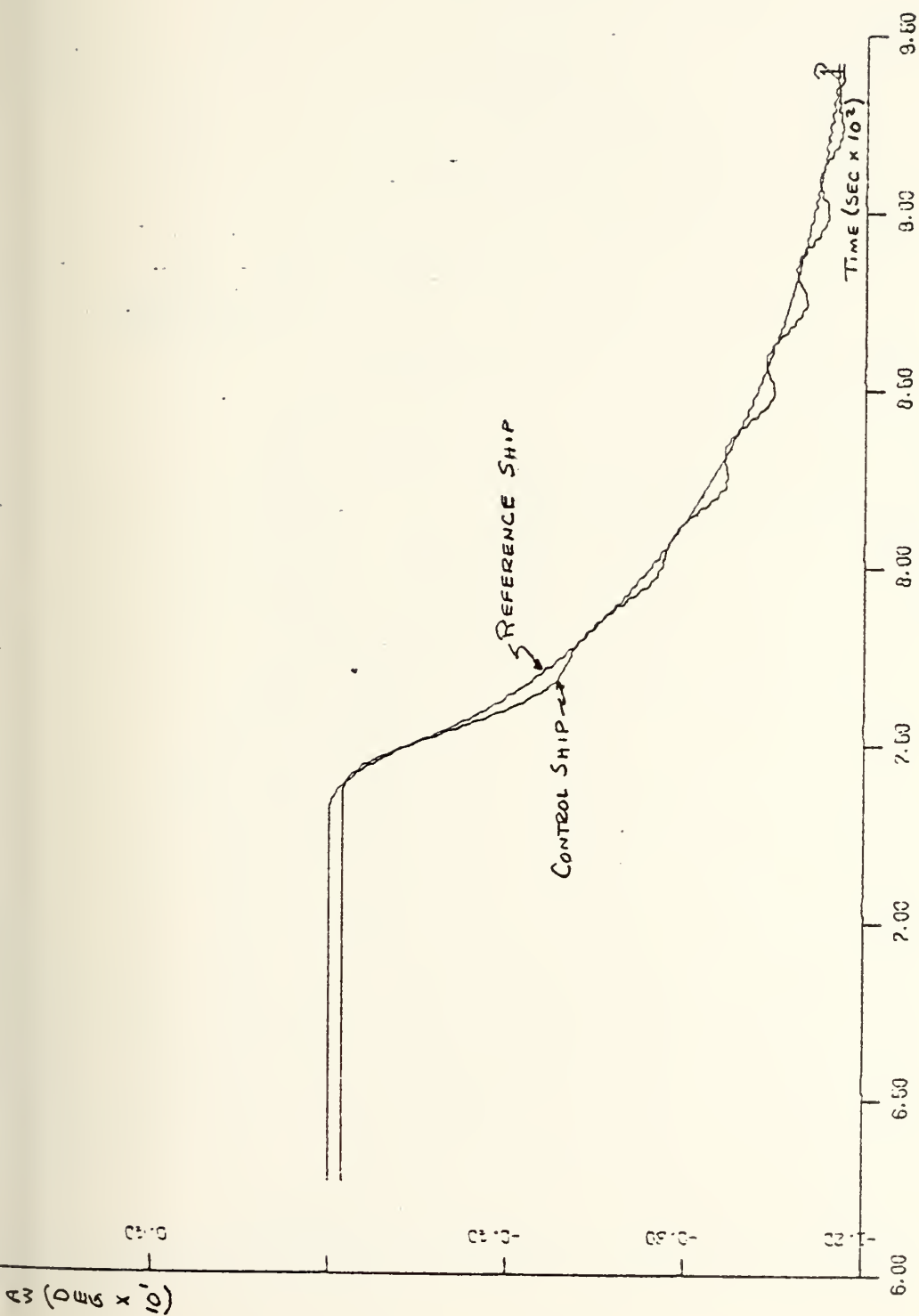


Figure III-56  
Turn Phase Run #6 Yaw Response

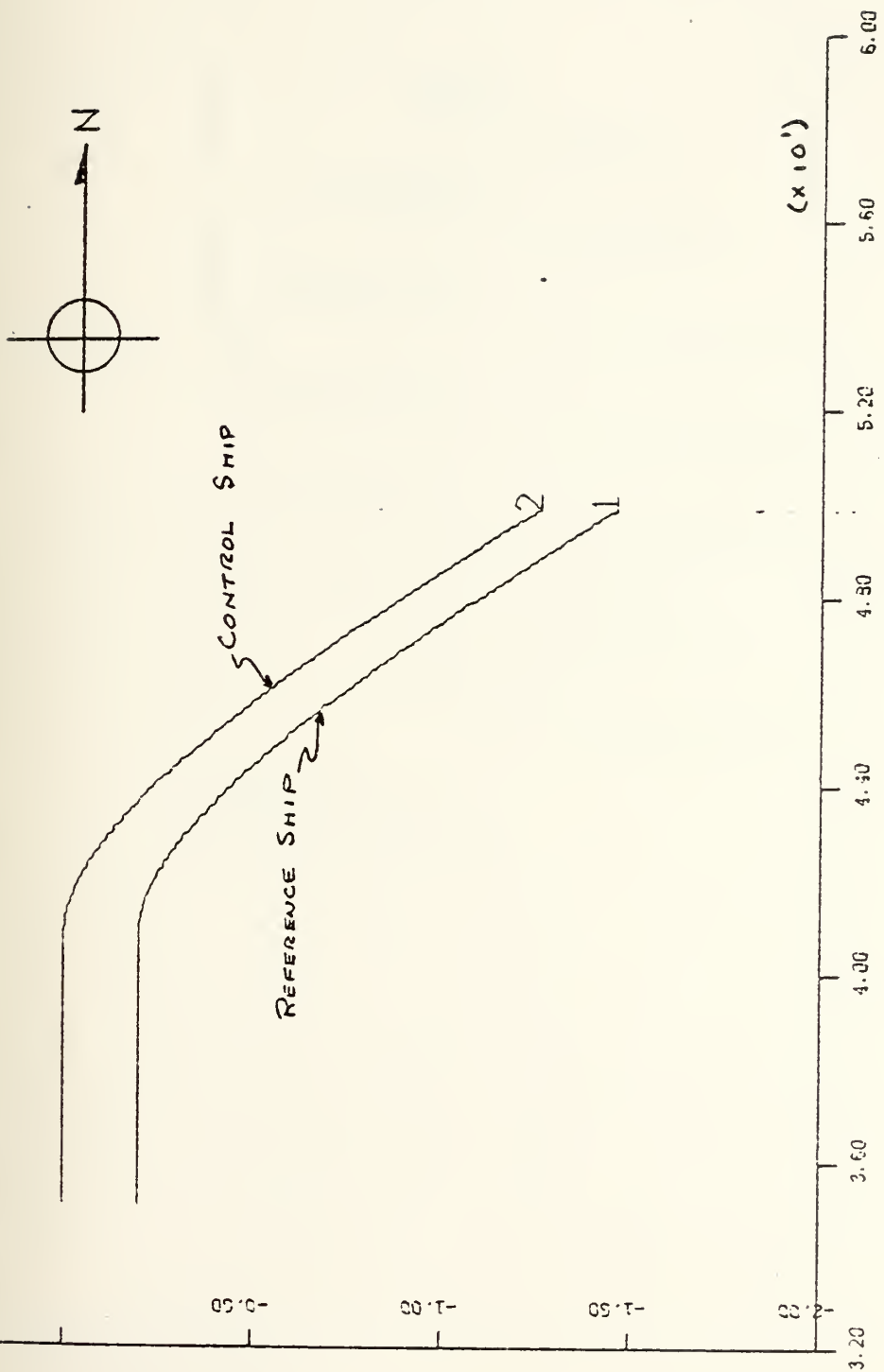


Figure III-57  
Turn Phase Run #6 Geographic Plot

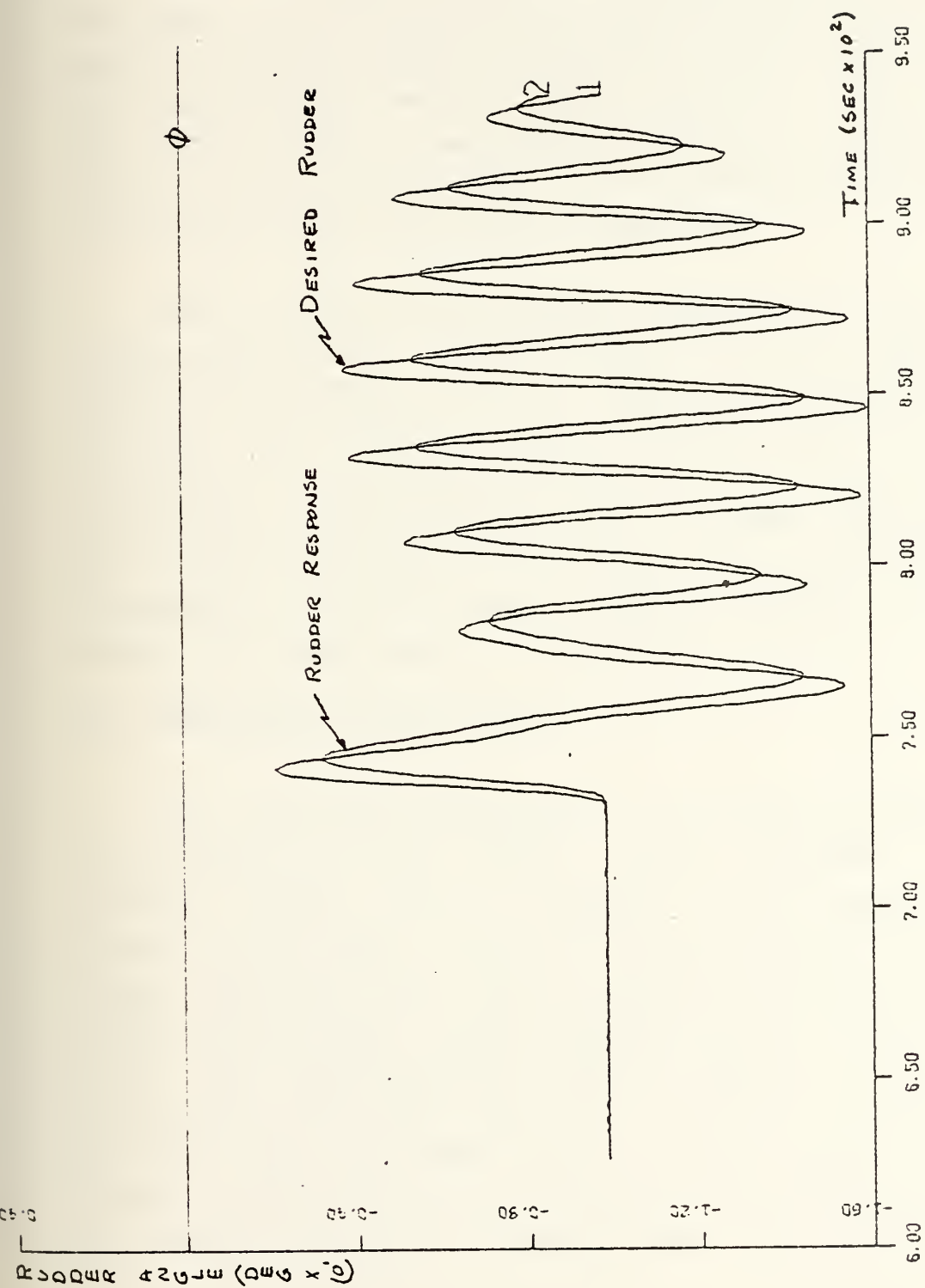


Figure III-58  
Turn Phase Run #6 Rudder Response

experienced which gives 1.6 ship lengths bow to stern clearance).

The purpose of run 6 is to provide simulation for an approach from the opposite side again disproving any concern for ambiguity in the trigonometric measurement scheme utilized. In all runs it must be emphasized that DD is the positive absolute distance desired and that IS provides the code flag for the desired side of approach. The system will work with DD set to some negative quantity; but the side of approach will reverse itself and the position placement will be correct, but on the side not desired.

Run 4 takes the desired distance in to 0.15 ship lengths (80.0 feet). This distance is usually the minimum desired by a prudent seaman. Again, even with this minimum distance, the control system performs up to desired standards. The importance of this run cannot be overlooked. Performance of the system at this extremum indicates that the gains utilized are correct for all expected conditions encountered in calm seas. Figures III-59 thru III-64 portray the remaining plots obtained in run 4.

#### h. Performance in Sea State

The calm sea performance of the heading control system is only part of the system testing required. Of even greater concern is the adequacy of the control when sea state is introduced. Section D.2. of chapter II models the three components of waves with two sinusoids and a small random impulse wave. These forces were introduced into the total RAS simulation as shown in computer program #7. In this program the wave length (WL) is set to one ship length and the wave direction (WD) is -015 degrees true. This scenario allows for a port turn into the prevailing sea as is common practice in experienced RAS evolutions. By

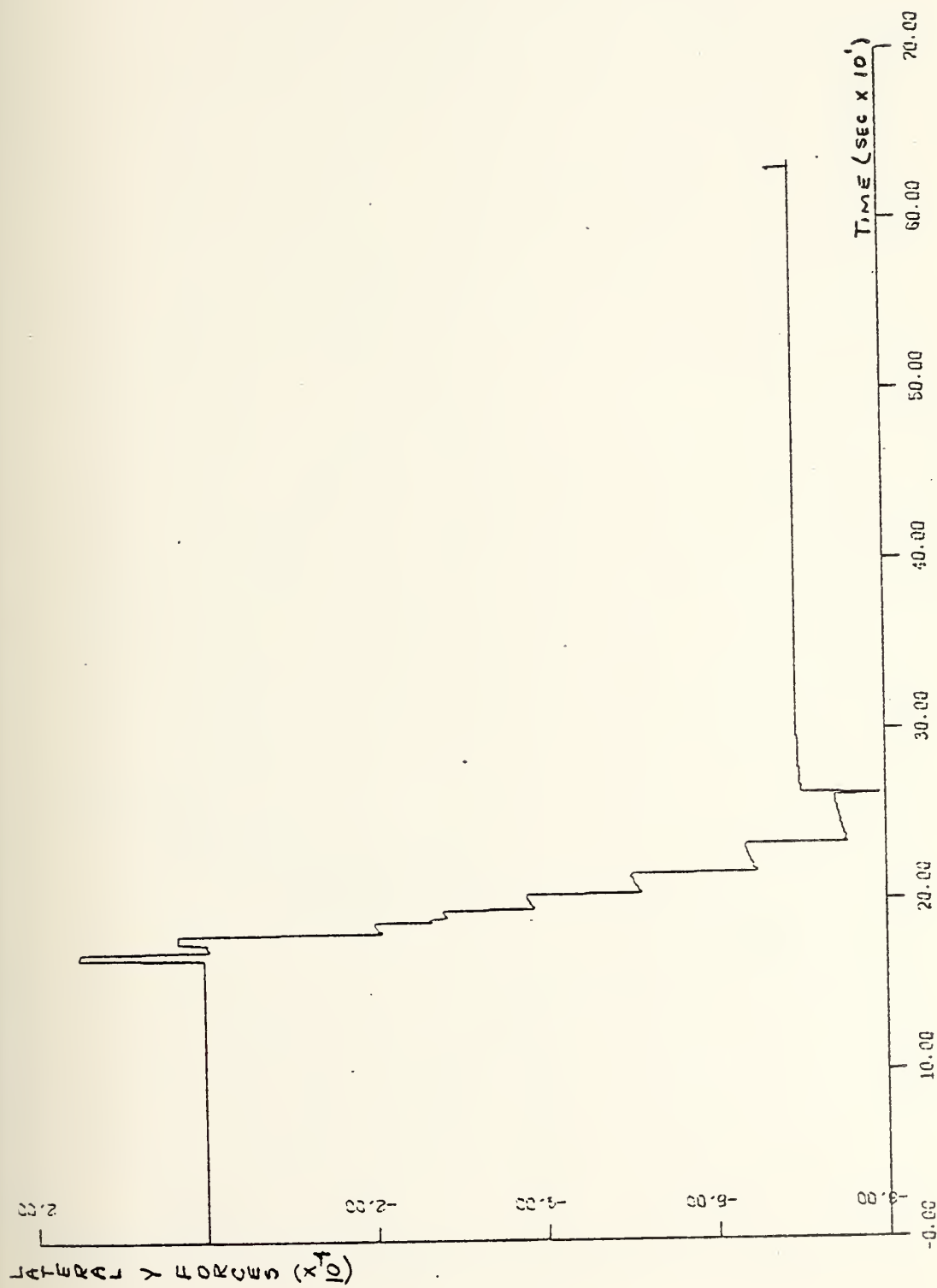


Figure III-59  
Approach Phase Run #4 Lateral Y Forces

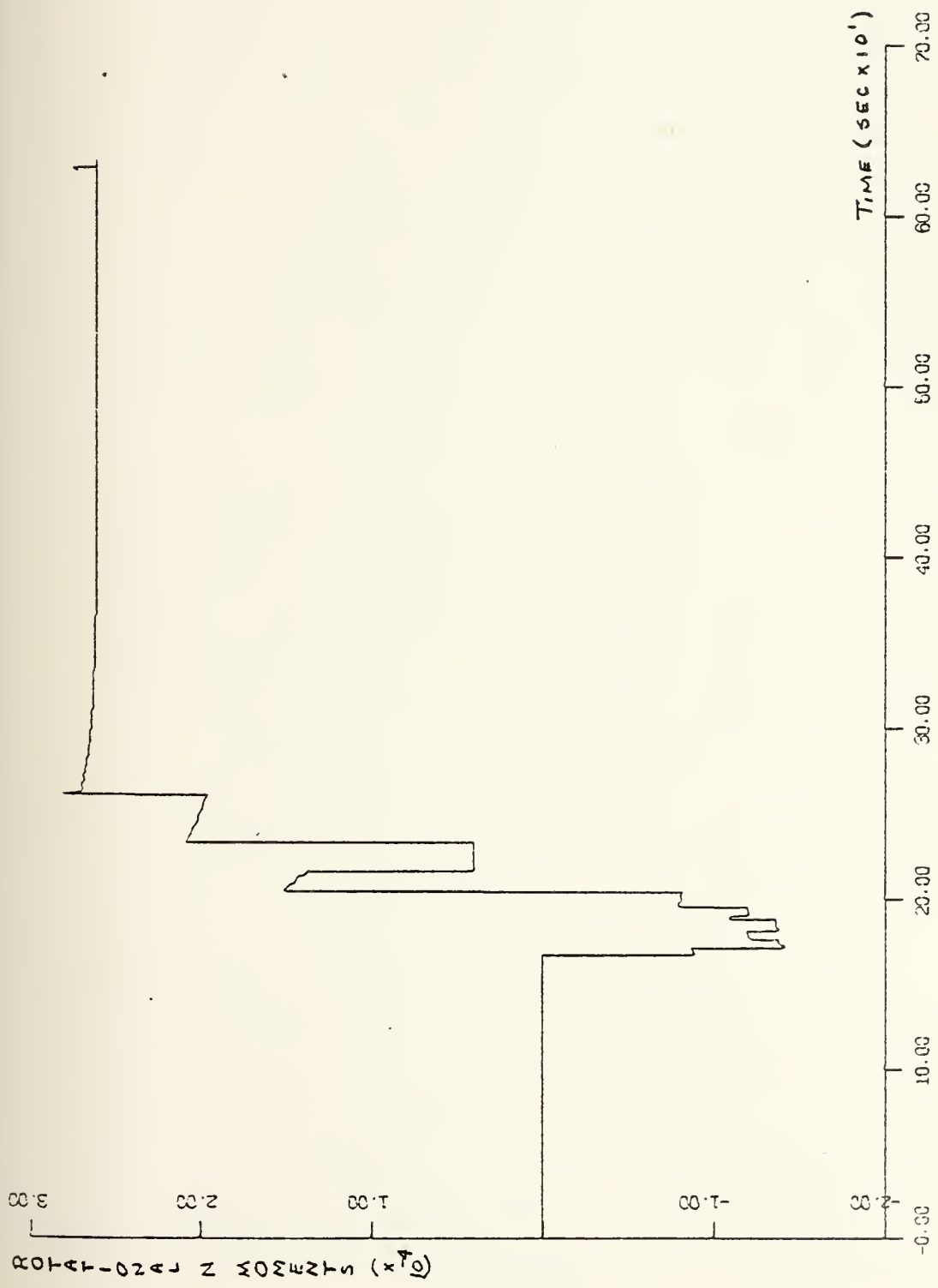


Figure III-60  
 Approach Phase Run #4 Rotational N Moments

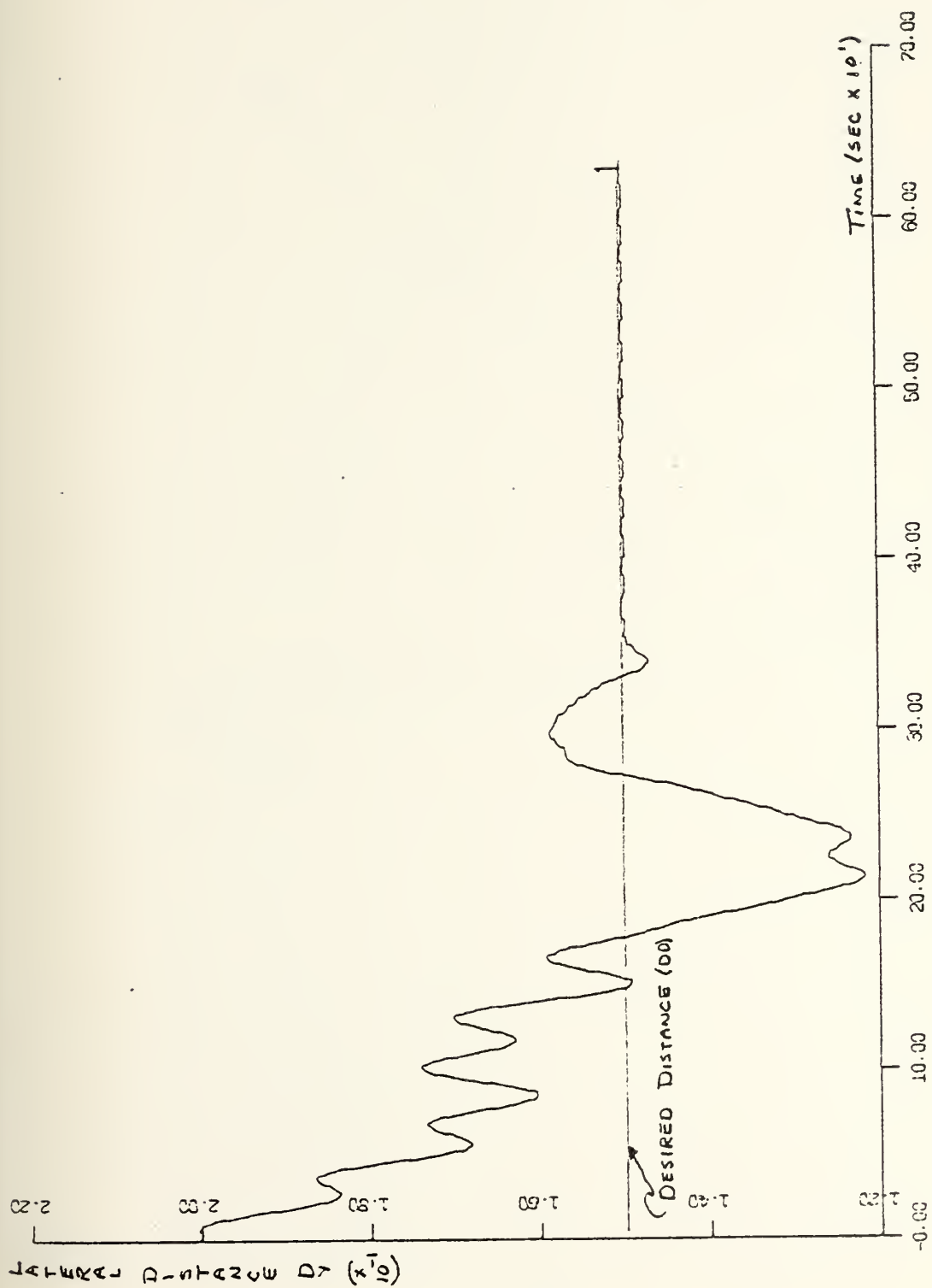


Figure III-61  
Approach Phase Run #4 Lateral Distance DY

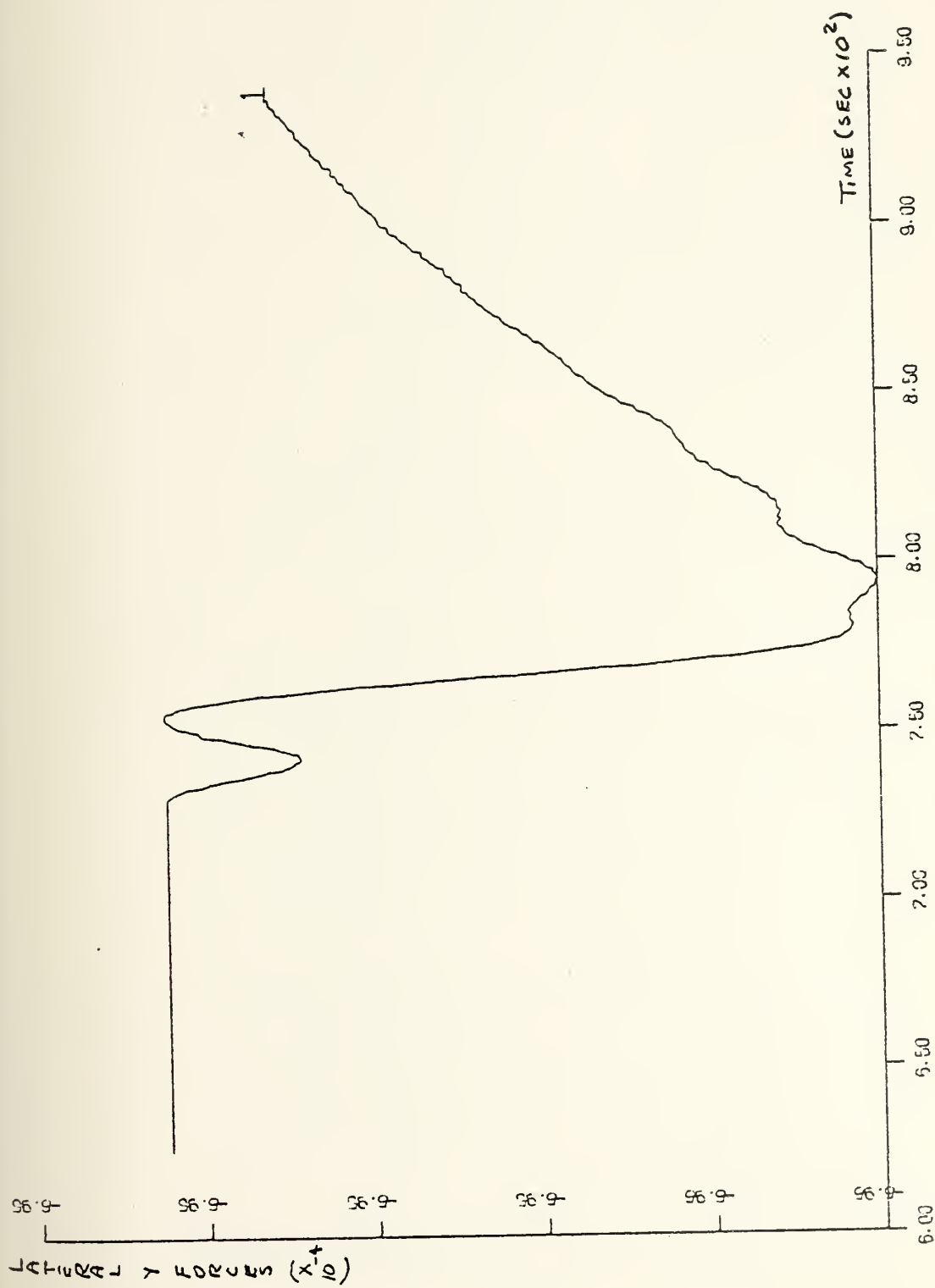


Figure III-62  
Turn Phase Run #4 Lateral Y Forces

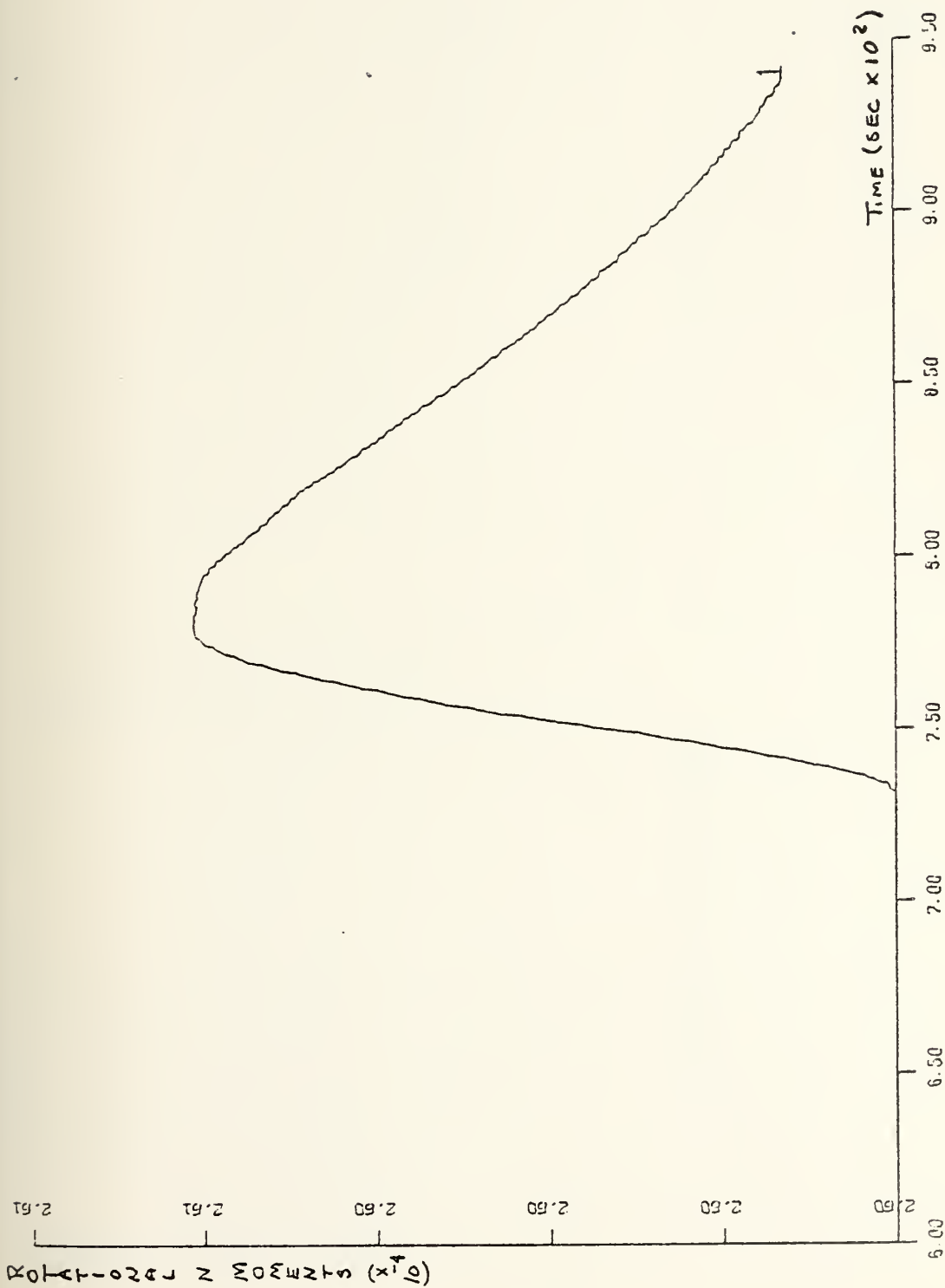


Figure III-63  
Turn Phase Run #4 Rotational N Moments

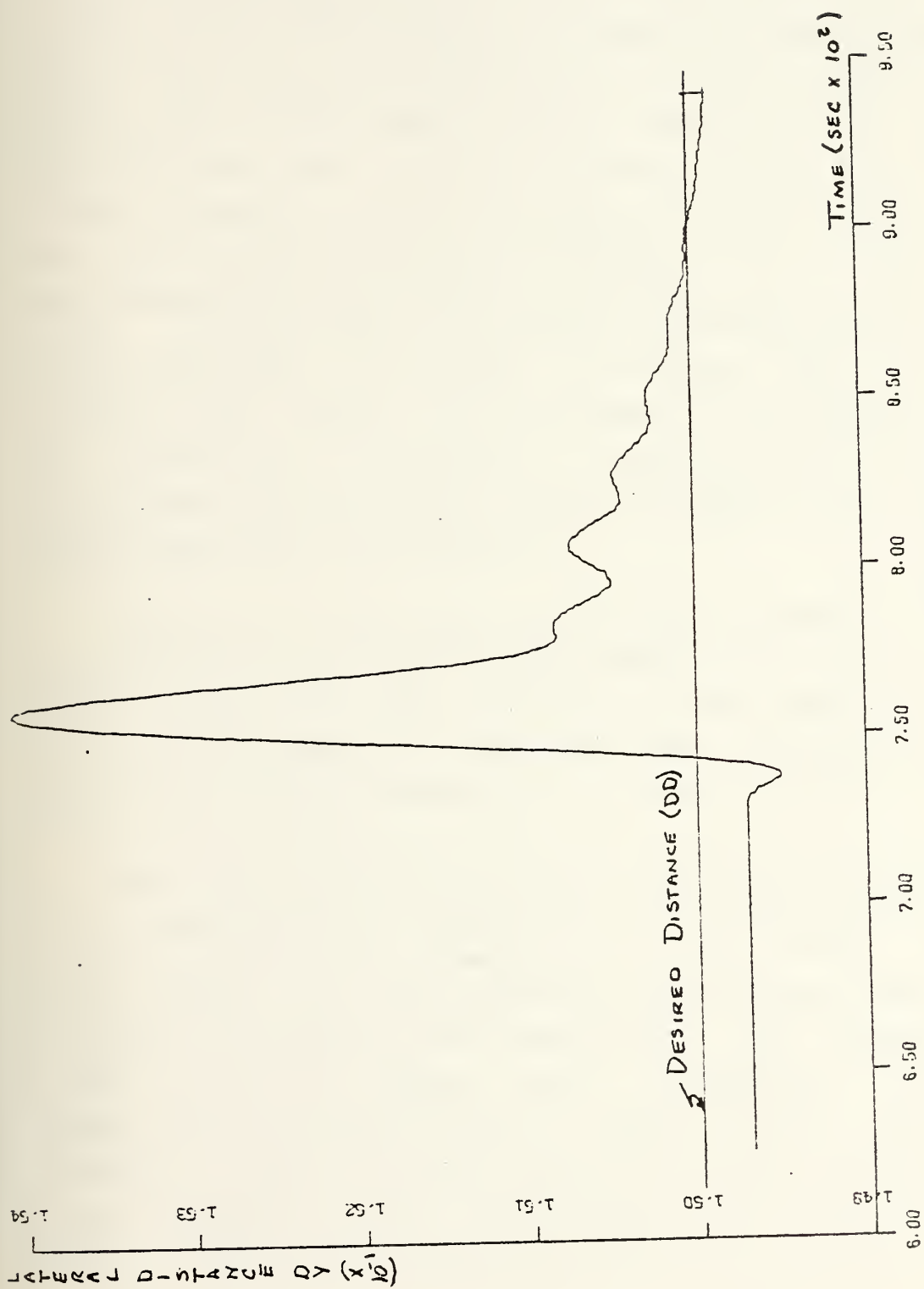


Figure III-64  
Turn Phase Run #4 Lateral Distance DY

minimizing the perturbation forces on yaw and lateral direction, a smoother RAS can be accomplished thus aiding safety and comfort during the actual transfer. The wave force maximum is taken as 0.05685. Runs were simulated which used maximum wave forces in the range 0.1137 to 0.05685, wave lengths from 0.5 to 1.5 ship lengths and wave directions 015 to -015 degrees off the initial replenishment course. The control system handled all of the perturbations well except for the cases of a wave length of 1.5. This length of wave with a force of 0.05685 exceeded the control systems capability in that the steady state conditions were not met before a turn was commenced. Figure III-65 shows this instability in the lateral distance DY of the turn phase. It is felt that the modeling inadequacies of the sea state development of chapter II coupled with a simple adaptive gain scheme are the source of the problem. This same phenomenon is covered in greater detail in the longitudinal position offset testing portion of the velocity control section of this chapter.

Problems of this type also manifest themselves in some cases when the wave force maximum (WFMA) was close to the 0.1137 value. If the sea state becomes excessive, which this value represents, a different gain schedule or, at best, a more complex adaptive gain scheme is called for.

The plots produced by computer program #7 are presented as a representative indication of the effectiveness of the control system in the presence of a sea state. Figure III-66 gives the yaw results of the approach phase which indicates the effect of the wave action. The corresponding rudder action of figure III-67 compensates to give the smooth lateral distance shown in figure III-68. The wave profile is shown in figure III-69 with curve 2 being WY and curve 3 being WN. Curve 1 is the WX profile which was not used in this run but will be utilized in the speed control

section later in this chapter. Similar curves are portrayed for the turn phase. Figure III-70 is the yaw difference between the two ships (remembering that the reference ship is not being perturbed by the interaction forces or the wave forces). Figure III-71 is the lateral distance  $DY$  maintained by the rudder response of figure III-72. The maximum lateral separation in the turn phase is 0.0037 ship lengths (1.95 feet). The wave profile is shown in figure III-73 with the same wave force curve sequence as the approach phase.

As can be seen from these plots, the control system operates very effectively in the presence of a sea state. Again, the development of a much more complex adaptive gain scheme is required to allow exceptionally high sea state. It is felt that the control system presented in this thesis is adequate for most situations that are encountered in the RAS environment. Only the extreme perturbations that chance would allow must be accounted for in a more complex adaptive gain scheme.

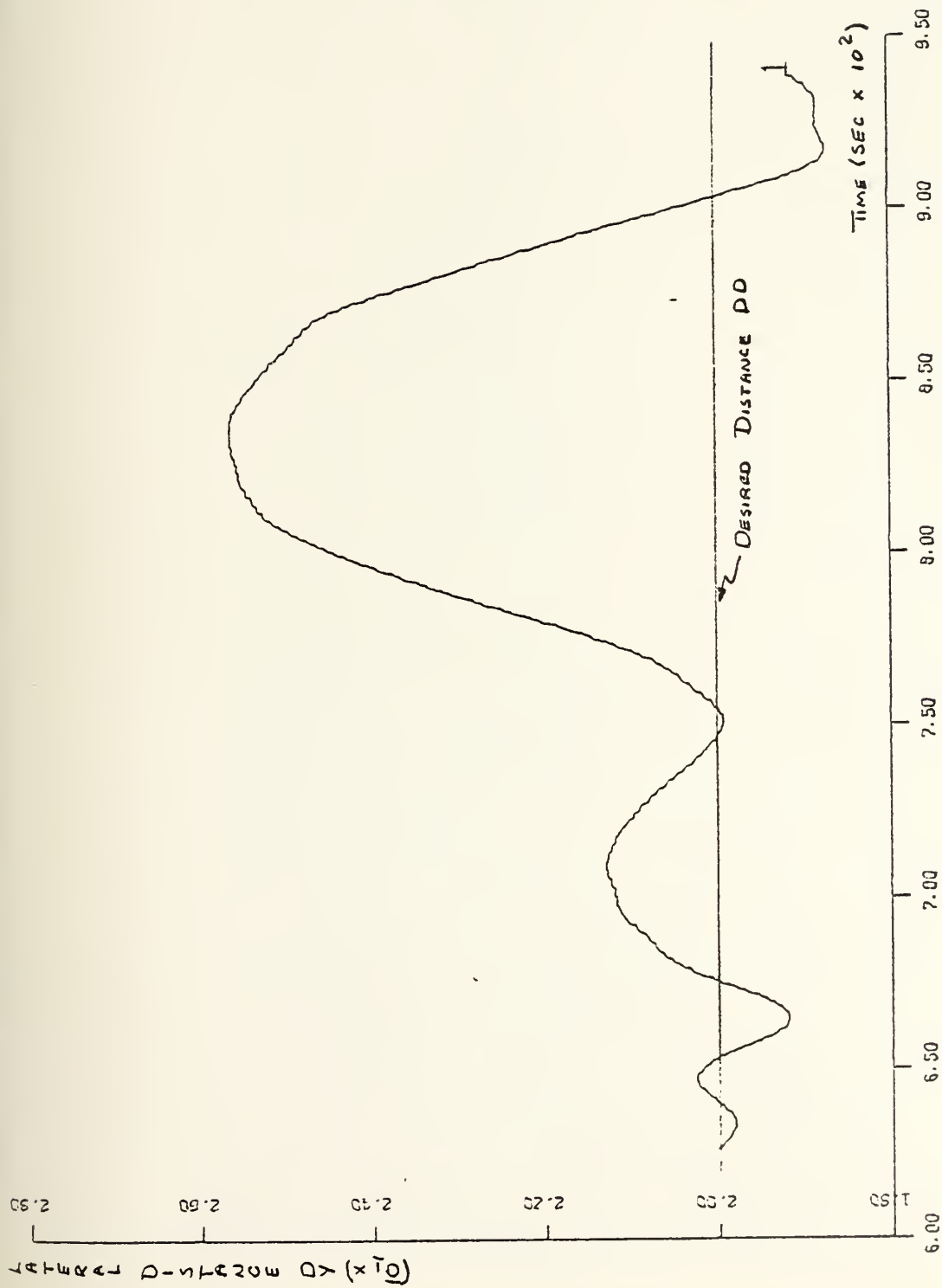


Figure III-65

Wave Effect on Turn Phase Lateral Distance (DY) WL=1.5

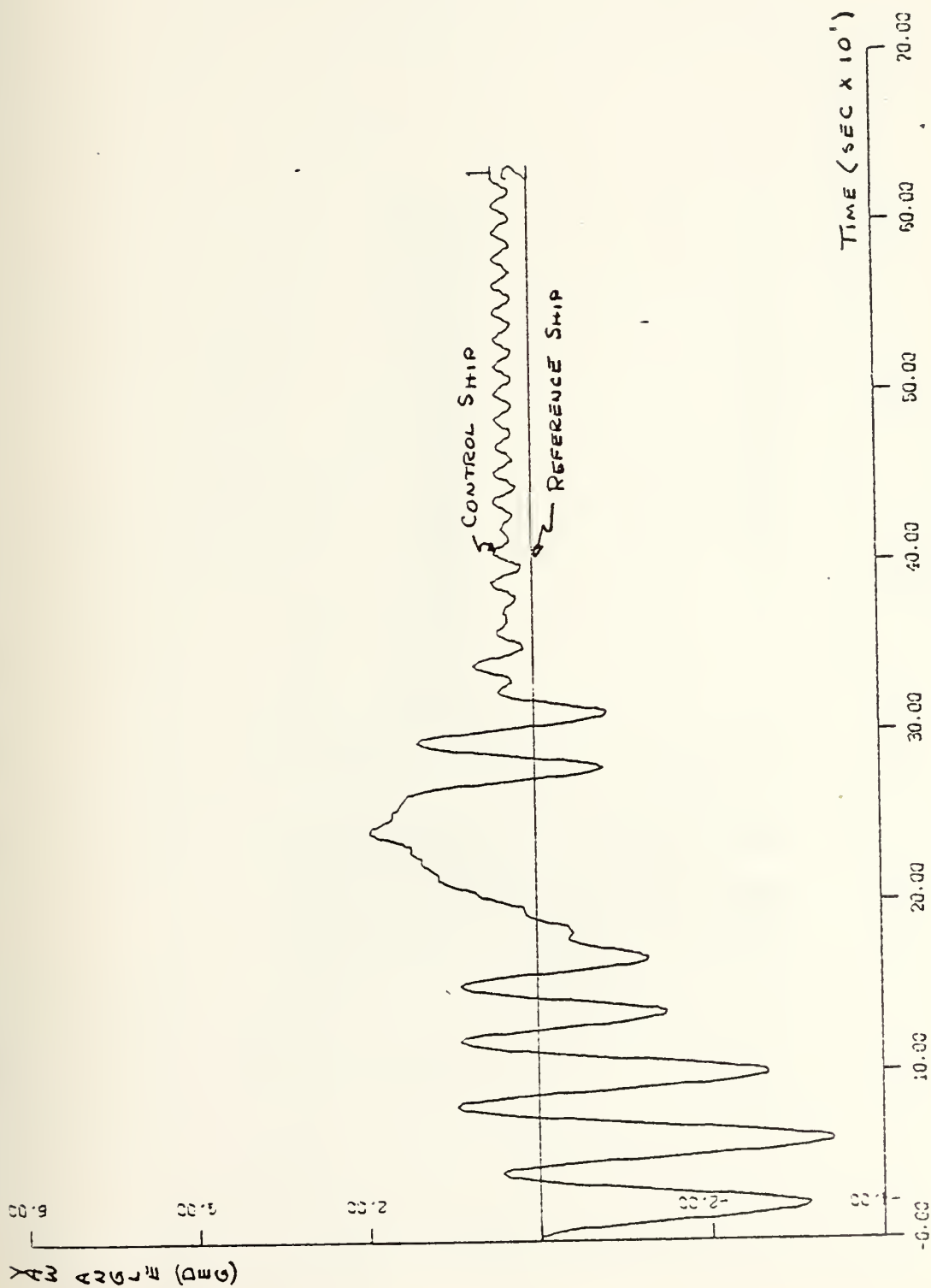


Figure III-66

Wave Effect on Approach Phase Yaw WL=1.0

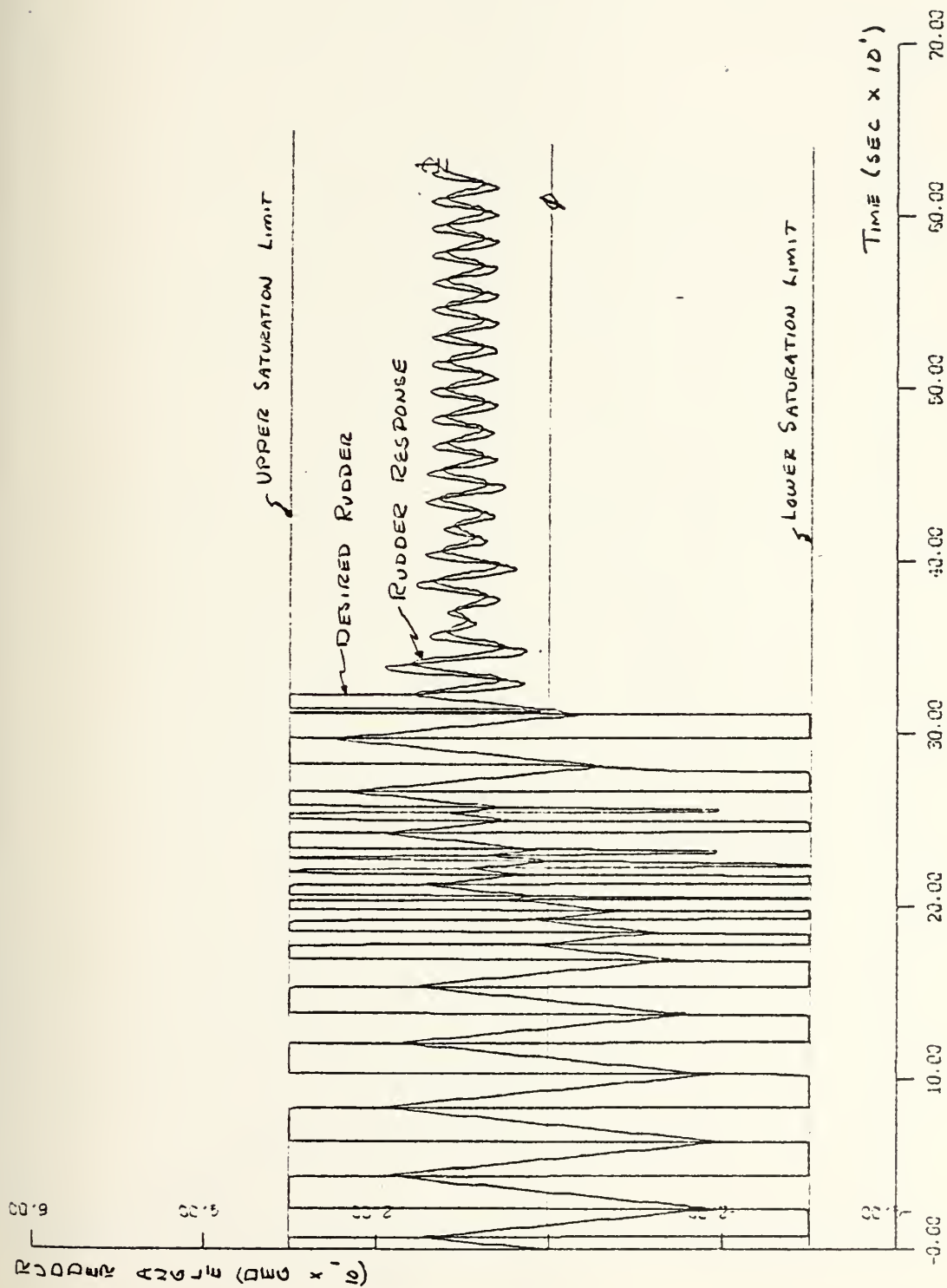


Figure III-67

Approach Phase Rudder Response to Waves WL=1.0

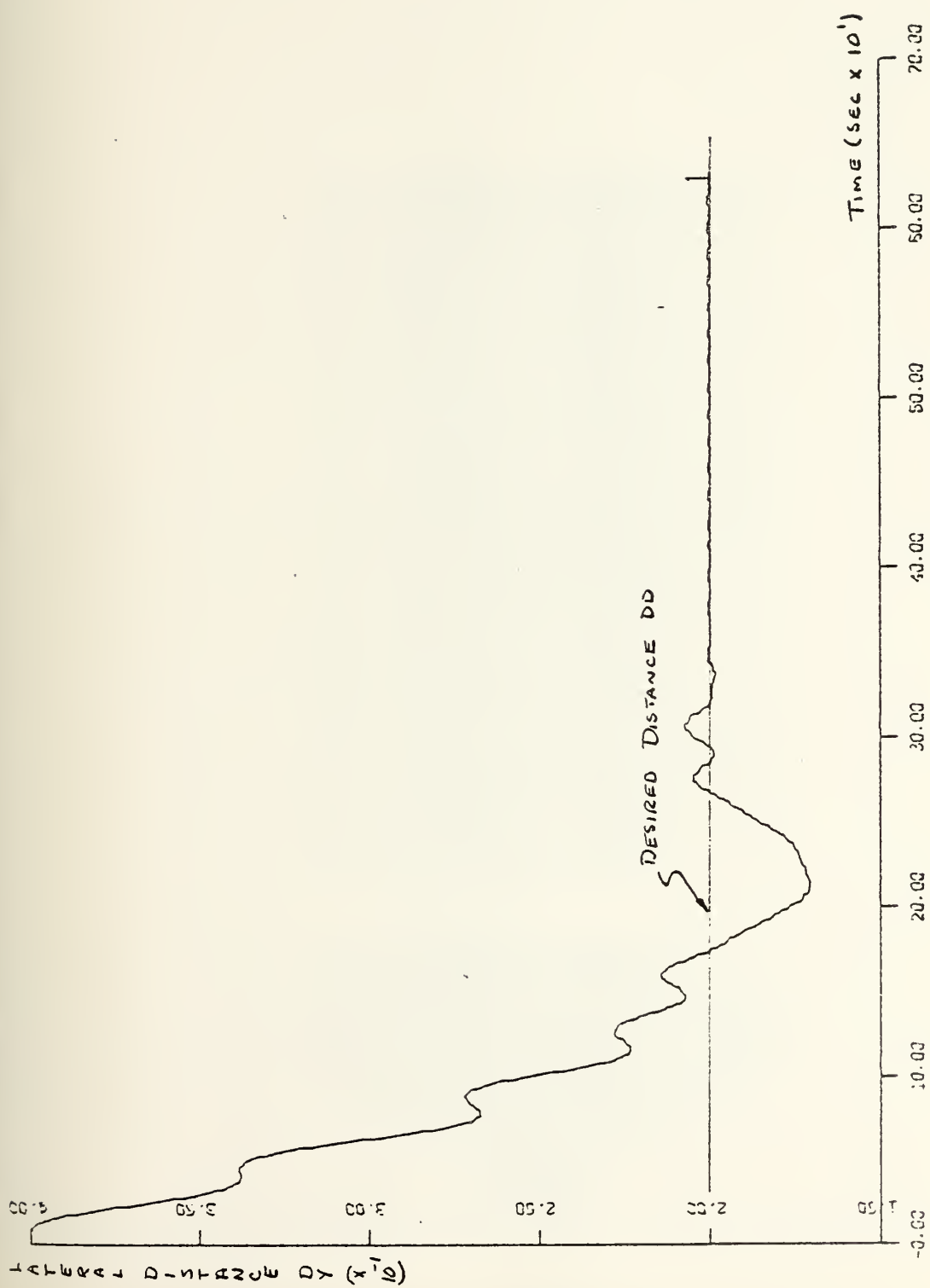


Figure III-68

Wave Effect on Approach Phase Lateral Distance ( $DY$ )  $WL=1.0$

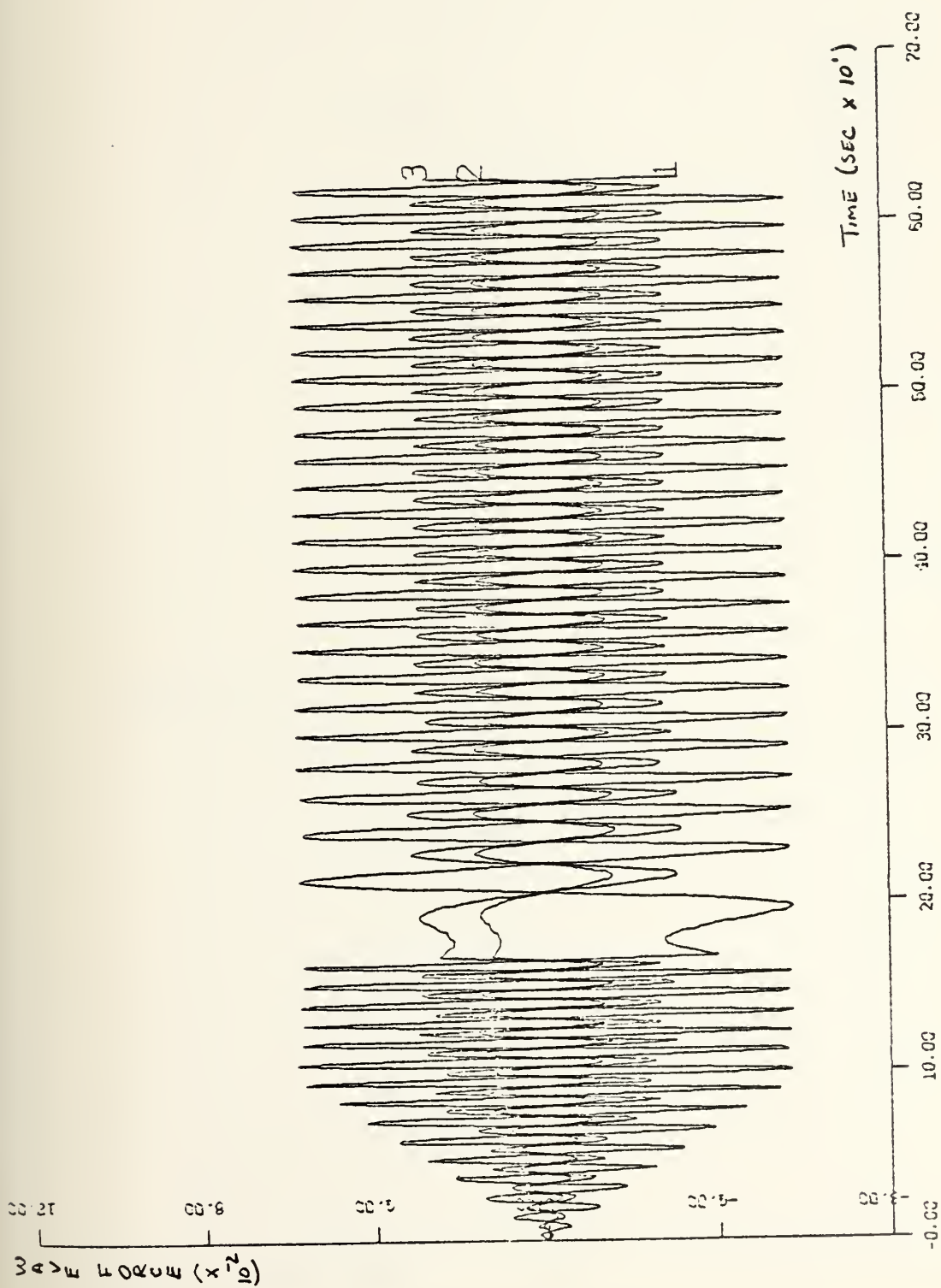


Figure III-69  
Approach Phase Wave Profile WL=1.0

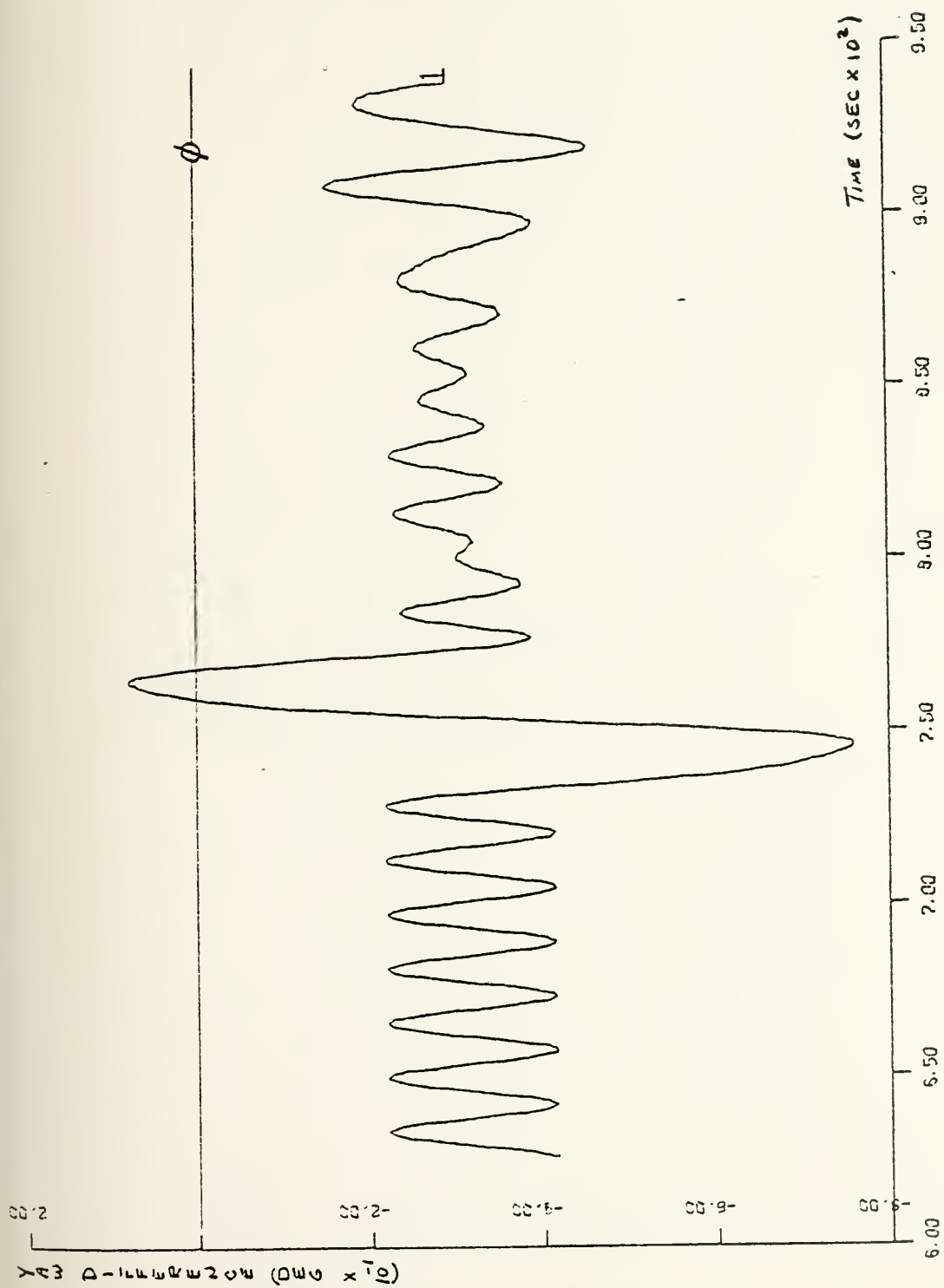


Figure III-70  
Wave Effect on Turn Phase Yaw WL=1.0

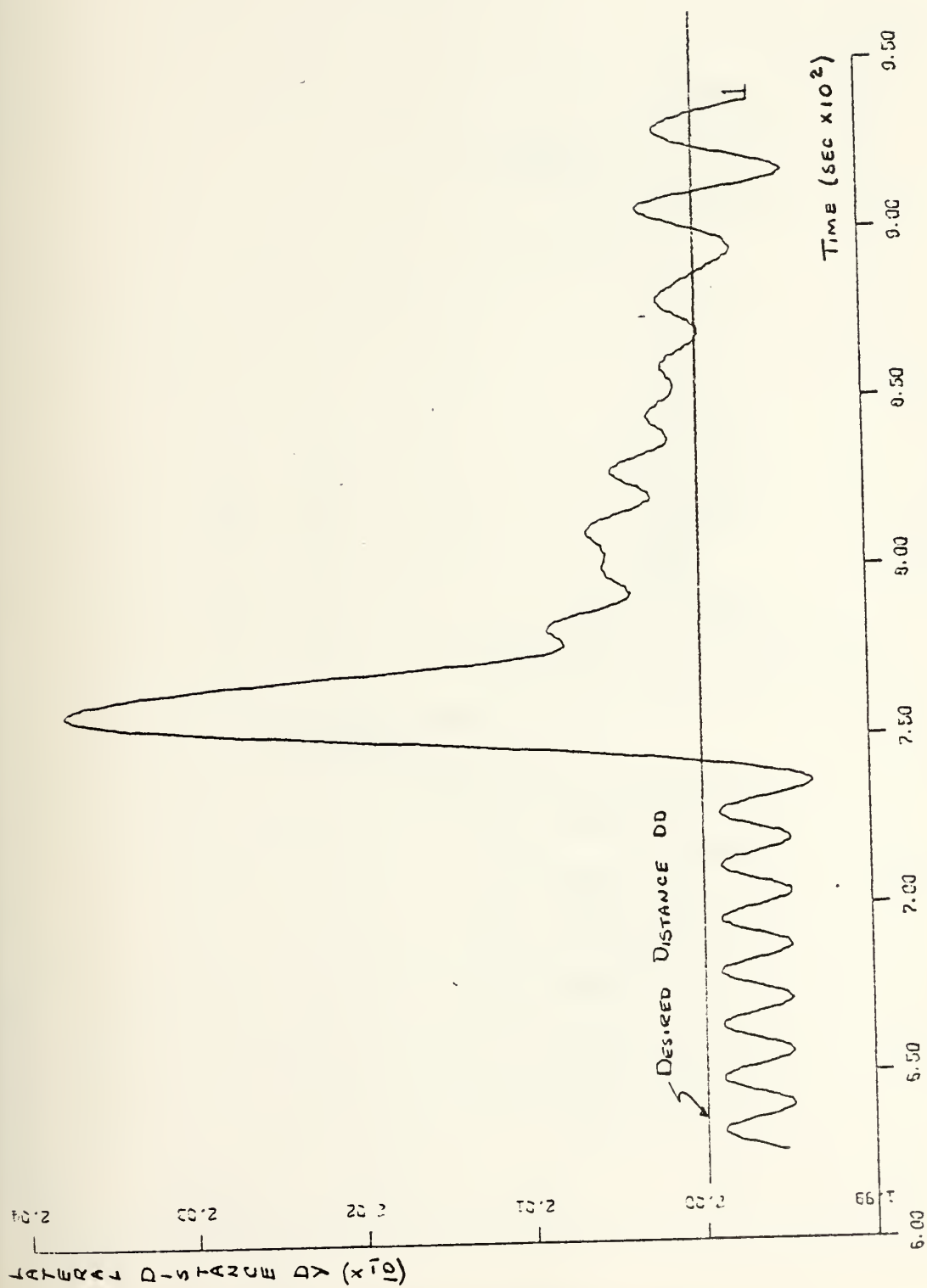


Figure III-71

Wave Effect on Turn Phase Lateral Distance (DY) WL=1.0

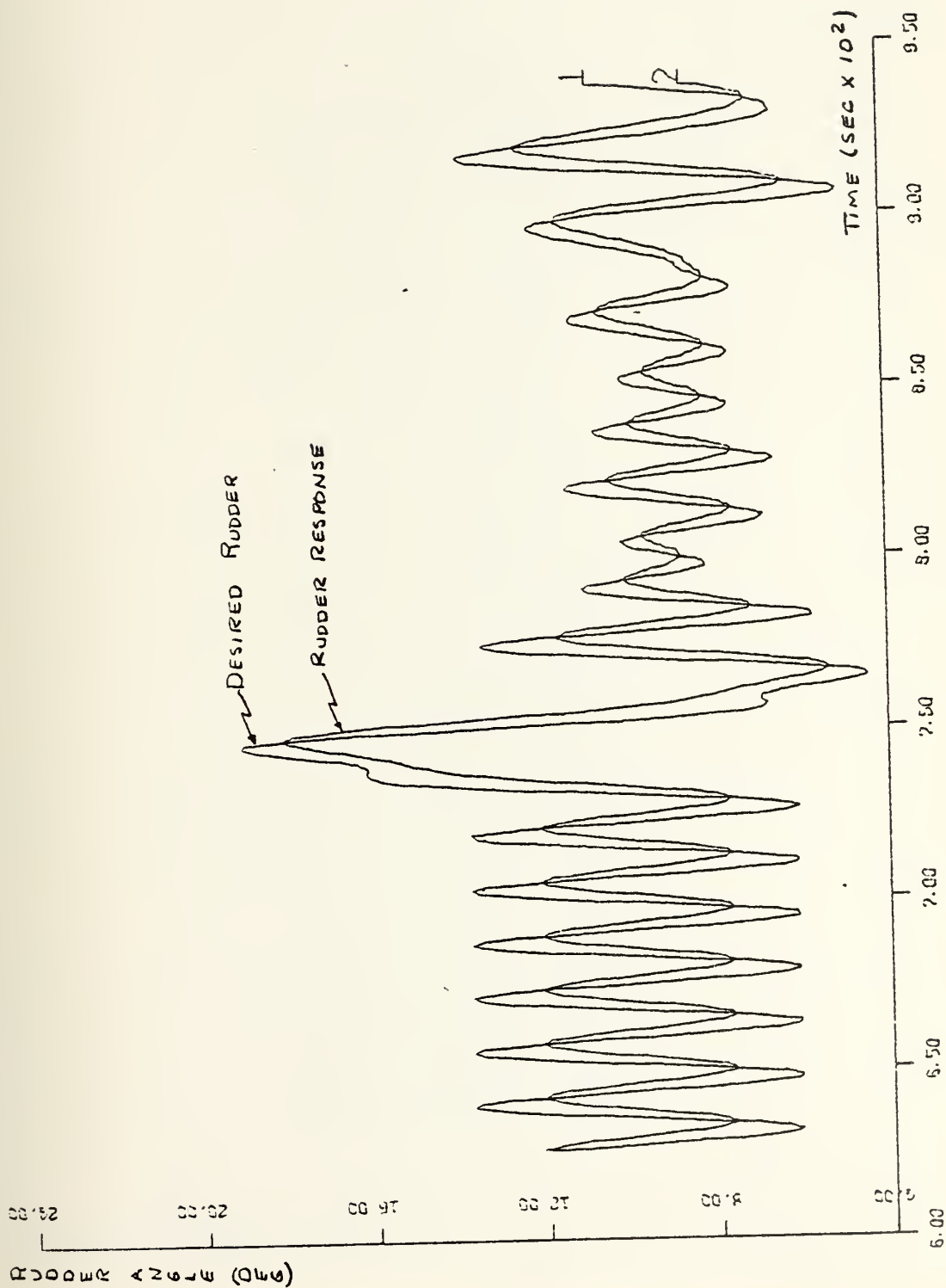


Figure III-72

Turn Phase Rudder Response to Waves WL=1.0

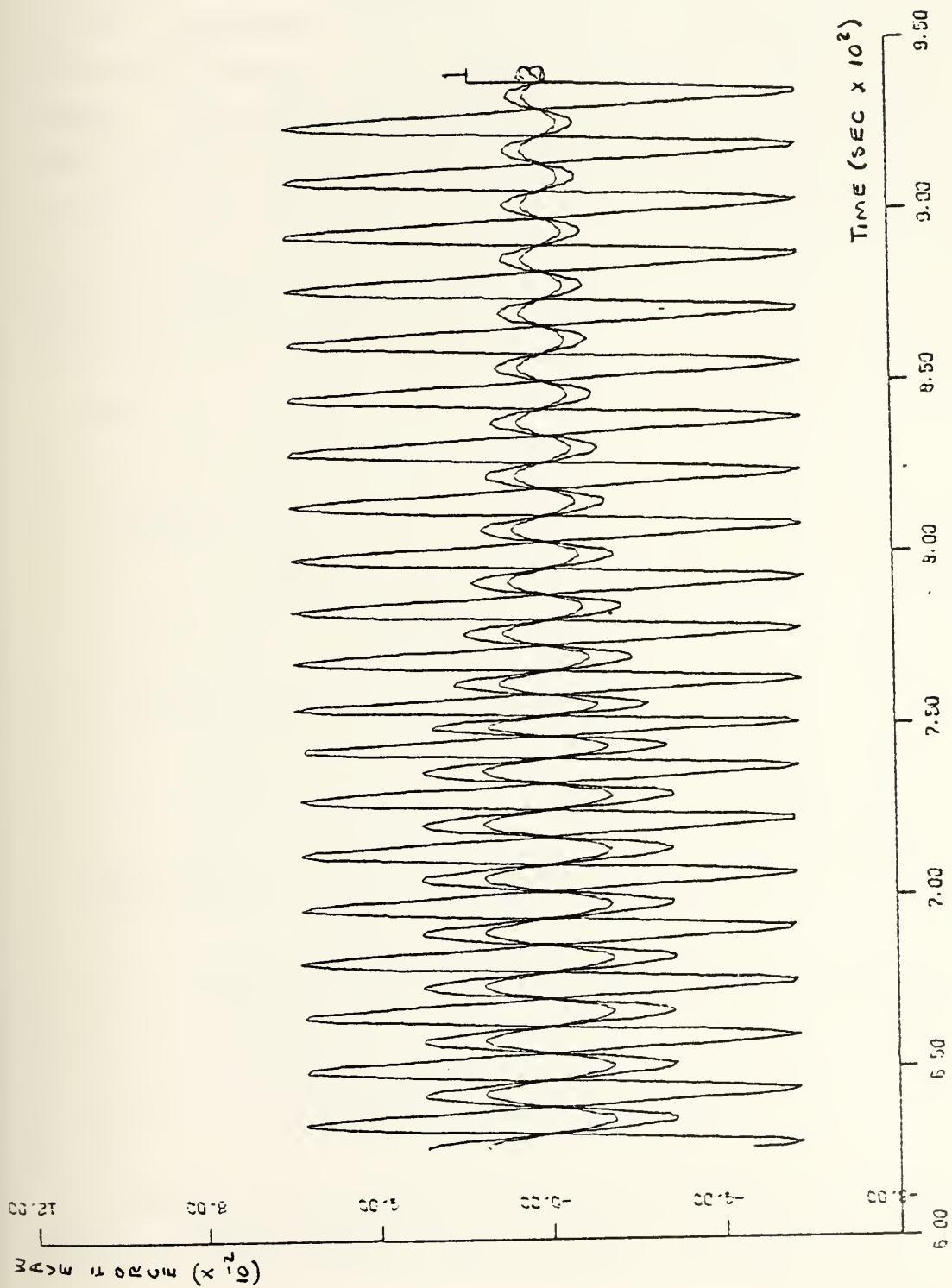


Figure III-73  
Turn Phase Wave Profile WL=1.0

## B. VELOCITY CONTROL

One advantage derived from using the linearized equations of motion is the decoupling of the velocity components from the remaining equations of motion. This allows separation of the design procedures for lateral separation control and velocity control. Section A of this chapter designed the lateral separation control using the simple speed control algorithm shown in figure III-74. This control output was used directly as the ship's speed (CDCT2) in the model simulation where no attempt was made to use the engine response developed in chapter II. Function SPDCTR of appendix A shows the control used.

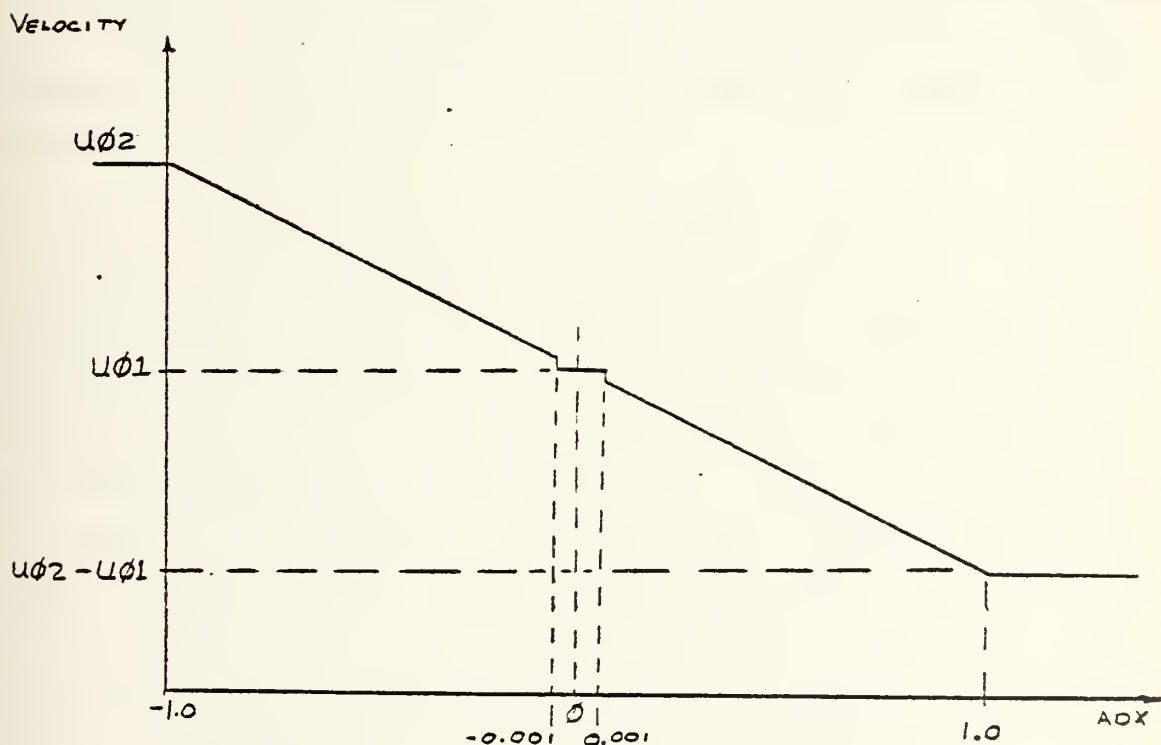


Figure III-74  
Non-optimum Speed Law

Because of this decoupling assumption, any valid approach speed control can be used, if used consistently,

for such a design. However, in the RAS environment, complete disassociation is not possible. Recombination occurs in the interactive forces and moments which depend upon the longitudinal distance as well as the lateral distance. Consequently, speed, which is directly responsible for the longitudinal distance, has a direct relation to the lateral distance attainment and maintainment.

The remaining parts of this chapter deal with the development of a viable speed control algorithm and the testing of the designed system.

### 1. Type of Control

Whenever two ships maneuver for replenishment at sea (RAS), the prime considerations are the time required for approach and the accuracy of position keeping plus conservation of fuel.

The nonlinear control law of figure III-75 is designed to maintain a preselected approach speed for minimum approach time. The proper location of the switching point increases the complexity of the solution since the time of switching from this speed is determined by the dynamics of the nonlinear position attainment loop. Once this position is reached, the speed controller is switched down to a linear portion of the control law to allow control for perturbations about the operating position. However, small perturbations about this operating point can be tolerated and, in fact, are desired to allow for conservation of fuel. Selection of this dead zone is wholly dependent on the accuracy required for final position. Figure III-75 indicates a dead zone extending to  $\pm 0.001$  normalized distance which in this case translates to  $\pm 0.53$  feet. Systems for which fuel considerations are not a motivating

factor may be designed without this part of the control law to allow finer tracking in the position loop.

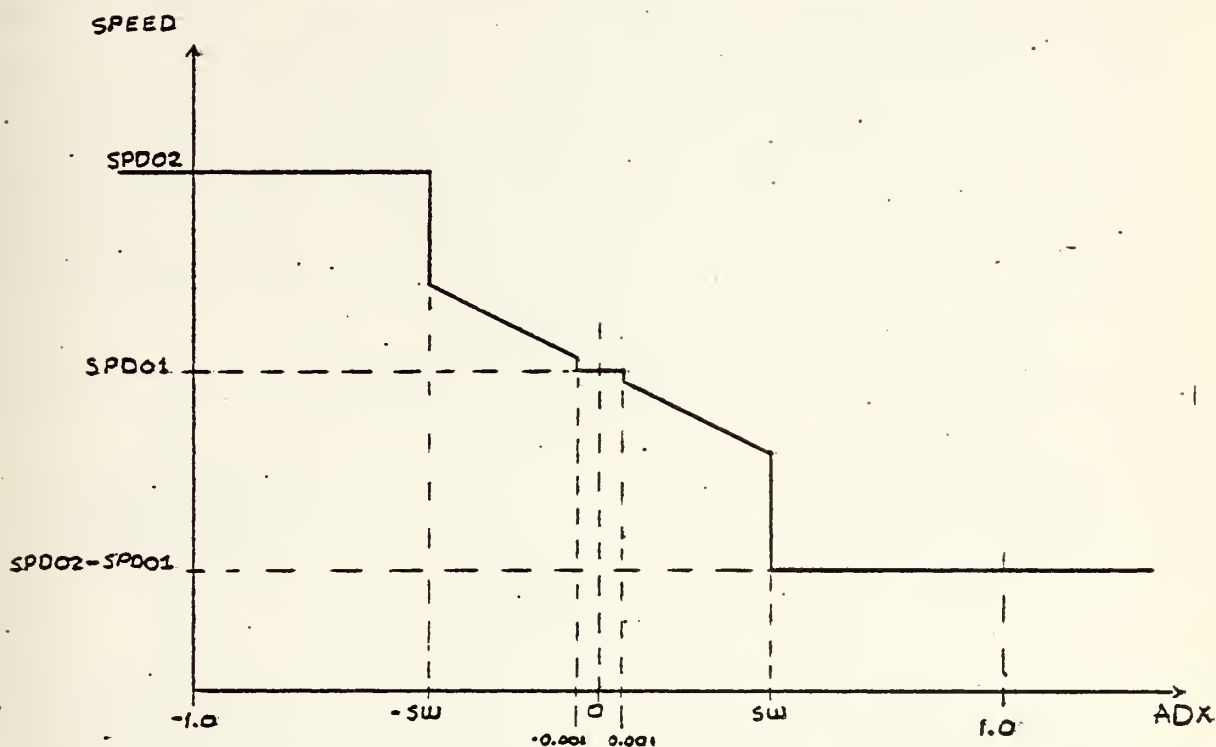


Figure III-75  
Speed Control Law

The speed control law as explained above is shown in figure III-75 for an initial approach speed of SPD02 and a final estimated reference speed of SPD01, with ADX being the dynamic position feedback defined as the longitudinal distance between centers of the ships referenced to the controlled ship's heading. Analytically, the linear portion of the control law is written as:

$$SPDCTR = -ADX \cdot (SPD02 - SPD01) + SPD01$$

Symmetric continuation of the control law accounts for operation on both sides of the operating point.

## 2. Optimization

Using this much simplified model of chapter II and the basic control law of figure III-75, the desired switching curve can be established. An optimization subroutine such as Subroutine BOXPLX can be used to iteratively obtain the optimum switching position (SW) for representative initial approach speeds. Figure III-76 is a flow chart of the subroutines and functions required for speed control

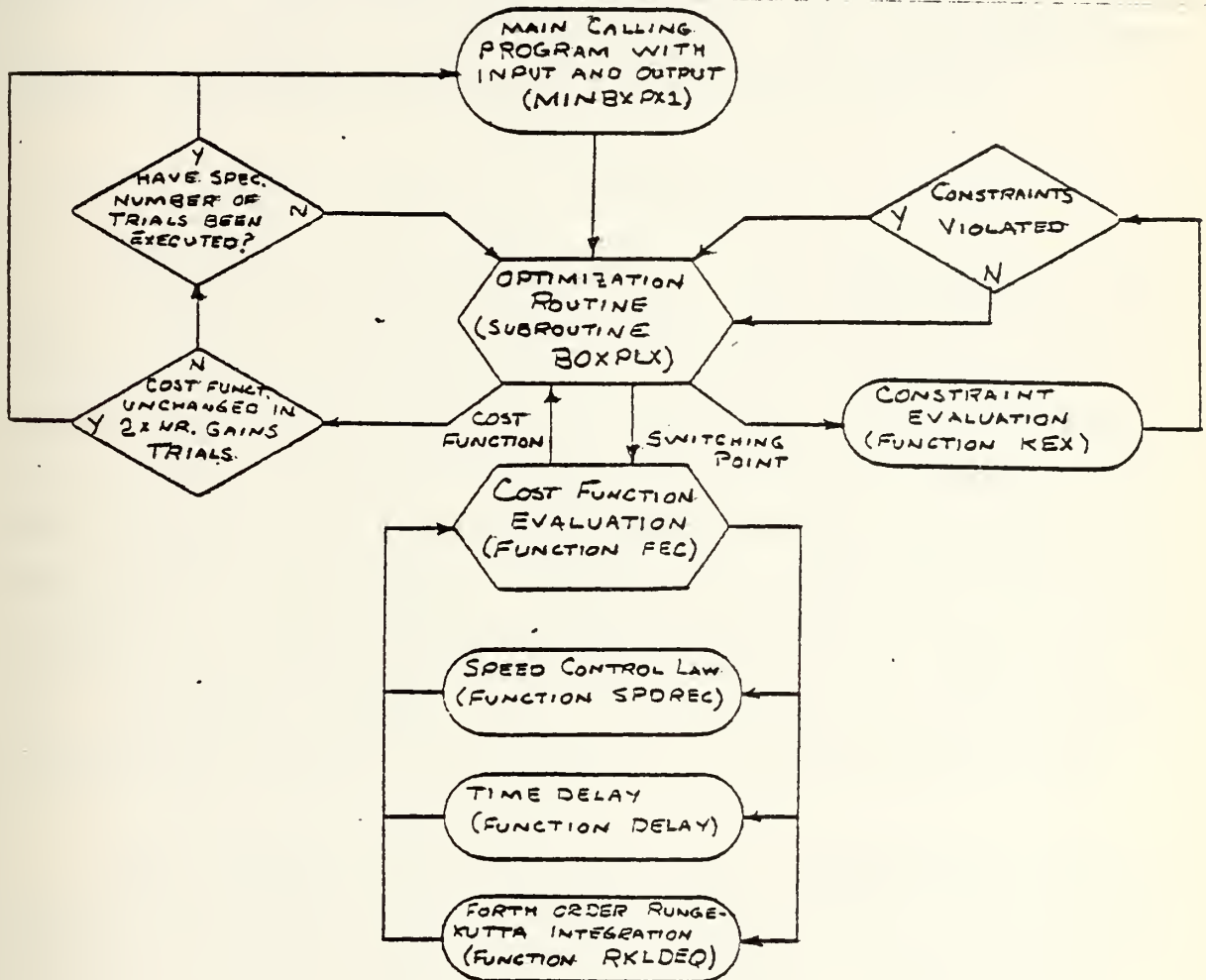


Figure III-76  
Optimization Flow Chart

optimization. The major merit of this nonlinear control law stems from the predetermination of the switching point for all possible conditions of initial speeds. This apriori

knowledge allows for offline computation of the switching position prior to commencing the approach. The cost function used for optimization is the ITAE which accomplishes two objectives. First, it forces the approach to be accomplished in minimum time. Secondly, it insures that the fuel expenditure will be optimized in the elimination of most overshoot and bang-bang control in the dead zone portion of the control law. The final value of the position error must be within the specified dead zone and the terminal speed must match the reference speed (SPD01). The cost function has the following form:

$$J = \int_{t_0}^{t_f} (t \cdot |ADX|) dt$$

Table III-4 is a comparison of the optimization runs with various initial speeds. The values shown for SW must be multiplied by the speed differential (SPD02-SPD01) to obtain the corresponding value of ADX. The max/min values show the band of values which produce the optimum cost. This range of values is attributed to the integration step size used in the optimization program. Experience with this particular optimization program indicates that erroneous values of the switching point are found if the step size is not carefully chosen. The step size may be adequate for integration, but not for location of the switching point.

The points obtained from the optimization runs are plotted in figure III-77. These points define the nonlinear switching curve which must be stored in the computer to insure optimal operation of the speed control for all approach speeds. From here there are many procedure options open. These options have as a goal some usable form for predicting the optimal switching point for any set of initial conditions. One may choose linear straight line segments with an interpolation routine, or a closed form switching curve polynomial. Due to the availability of a

INITIAL CURVE POINTS					
SPDO2	SPDO1	SW MAX	SW MIN	SW	COST
1.1	1.0	.545 *	.545 *	.545	22.340515 **
1.2		.58705	.58424	.585	5.733367
1.3		.62656	.6256	.626	2.700768
1.4		.6845	.68234	.683	1.672599
1.5		.73169	.7283	.729	1.223071
1.6		.7644	.76142	.763	0.992283
1.7		.7945	.7926	.7936	0.861552
1.8		.82178	.81945	.82	0.774621
1.9		.8501	.8439	.85	0.757244
2.0		.8673	.86375	.865	0.730168
CURVE CHECK POINTS					
1.5	1.1	.6859	.6823	.683	1.668055
1.5	1.2	.6307	.6297	.6302	2.691659
1.6	1.2	.67965	.67906	.6793	1.659956

\* cpu usage over 4 min. - run not complete.

\*\* cost function based on 20 min problem time  
all others based on 10 min problem time.

Table III-4  
Optimization Results

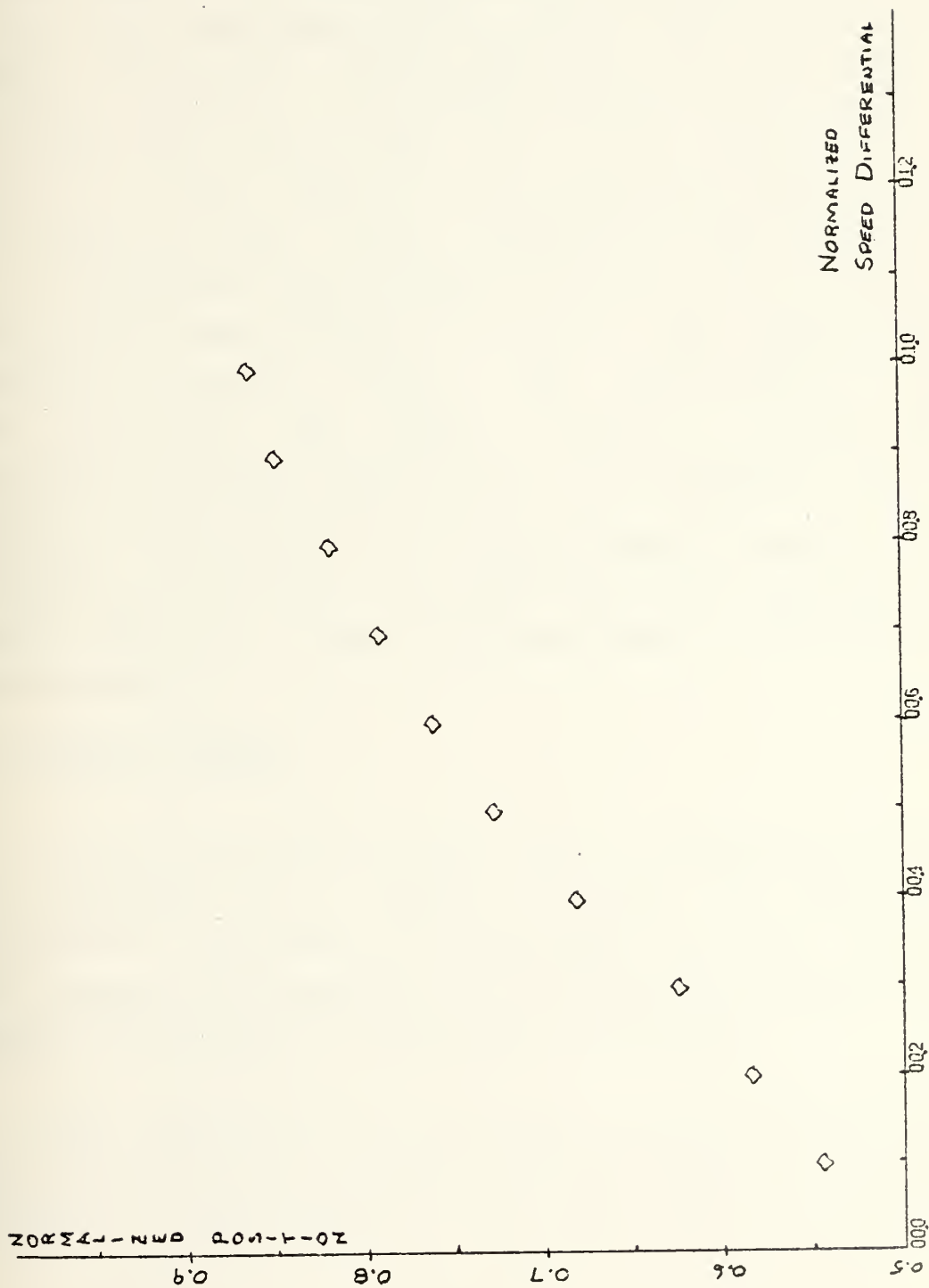


Figure III-77  
Switching Curve Minimization Results

hybrid configured XDS 9300 digital computer and AGT-10 graphics terminal, the latter course was taken.

A polynomial curve fitting algorithm was used to obtain the required polynomial coefficients of best fit. This was done for polynomials of order 1 thru 5. The coefficients and the sum of the squares of deviation from the original points are tabulated in table III-5. The selection of the order to be used is highly dependent on the degree of accuracy required. In the RAS problem, the average error introduced for a first order fit is 8.0 feet(1.07 sec), while the fifth order fit introduces an average error of 1.35 feet(0.180 sec). Prior acceptance of errors introduced by an integration (and problem) step size of 0.8 sec allows for use of a second order fit without any degradation of simulation accuracy [second order average error is 2.848 feet (0.38 sec)]. The graphic display of figure III-78 indicates very little difference in the switching curves for second to fifth order polynomial fits. For the sake of accuracy, and owing to the computer control methods of this thesis, the fifth order polynomial fit shown separately in figure III-79 is used for determination of the switching point location.

### 3. Control Testing

A true test of the control law is accomplished when it is introduced in a computer program for a complete RAS simulation. Considering the performance of this controller in a complex environment of full scale RAS simulation allows maximum verification of the controller design.

The scenario for this simulation initially positions the ships such that the ship being controlled starts an approach 5 ship lengths (2639 feet) behind the reference

POLYNOMIAL DEGREE	COEFFICIENTS OF POWER:						SUM OF SQUARES OF DEVIATION
	5	4	3	2	1	0	
1					0.367928	0.524	$2.2911 \times 10^{-3}$
2				-0.194621	0.582011	0.481	$2.9117 \times 10^{-4}$
3			-0.174164	0.0927511	0.449472	0.496	$1.9748 \times 10^{-4}$
4		0.748543	-1.82096	1.29791	0.120113	0.521	$1.0517 \times 10^{-4}$
5	-2.24869	6.93243	-8.04233	4.08065	-0.409977	0.554	$6.5732 \times 10^{-5}$

Table III-5  
Polynomial Curve Fit Results

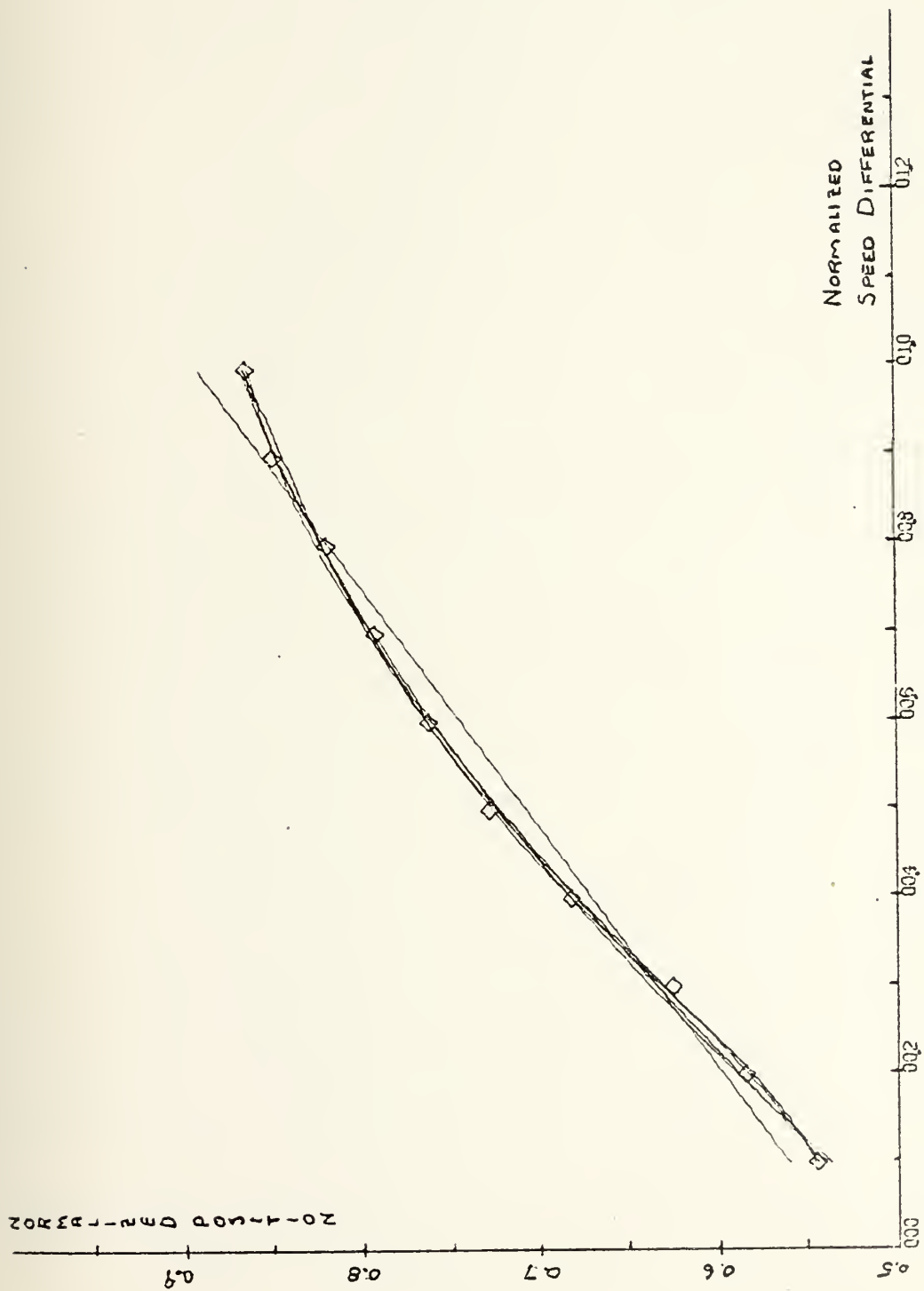


Figure III-78  
First Thru Fifth Order Polynomial Curve Fit Results

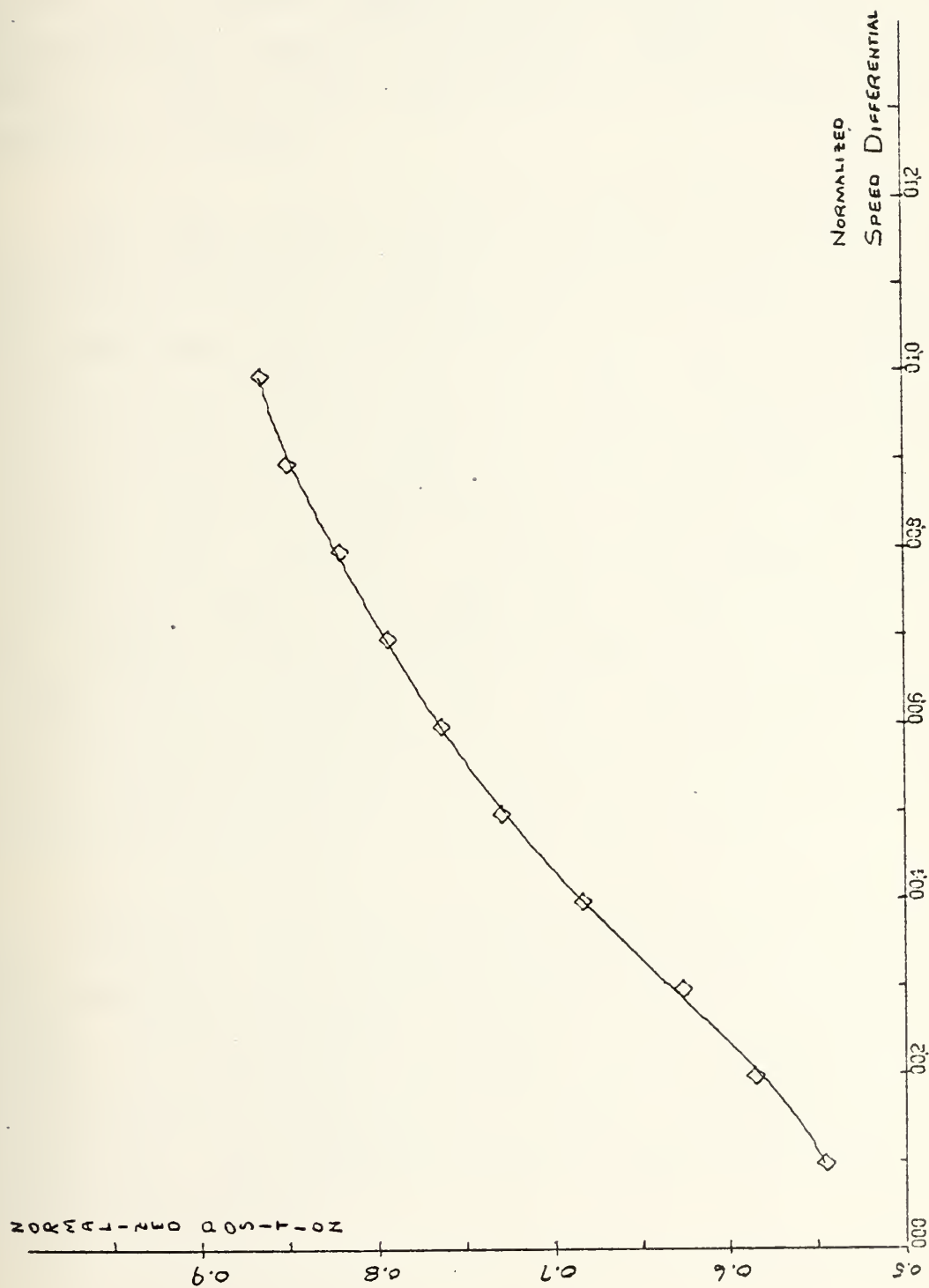


Figure III-79  
Fifth Order Polynomial Curve Fit

ship and displaced 0.4 ship lengths (211 feet) to the right. The desired final position is alongside and displaced 0.2 ship lengths (106 feet). The heading control system used is developed in section A of this chapter.

The approach phase is accomplished with the speed desired and speed acquired shown in figure III-80 with the corresponding position attainment exhibited in figure III-81. These plots show excellent switching and optimal position attainment.

The next step is to insure that the position keeping loop will maintain the desired position with an induced perturbation. This is accomplished by turning the reference ship away from the control ship a total of 15 degrees to observe the reaction of the speed control loop. The reference ship's turn causes the relative motion between the ships to be altered, making the control ship lag the desired position. The nonlinear control system is designed to correct this situation as soon as the actual position is outside the limits of the dead zone. Figure III-82 displays the desired speed and acquired speed for the control ship. Figure III-83 indicates that the corresponding position deviates from the desired by 0.0154 ship lengths (8.13 feet) at the maximum excursion. This is well within the limits of acceptability for such a drastic perturbation.

The introduction of velocity control was accomplished by combining the simplified engine response of chapter II and the speed control law developed here. By setting the speed desired (SPDDES) equal to the output of Function SPDREC and scaling the speed error (SPDERR) to the nondimensional equations of motion, the velocity loop is initiated. The auxiliary equations added to those presented in chapter II are:

Figure III-80  
 RAS Speed Control Approach Phase  
 Speed Desired (1) and Speed Acquired (2) vs Real Time

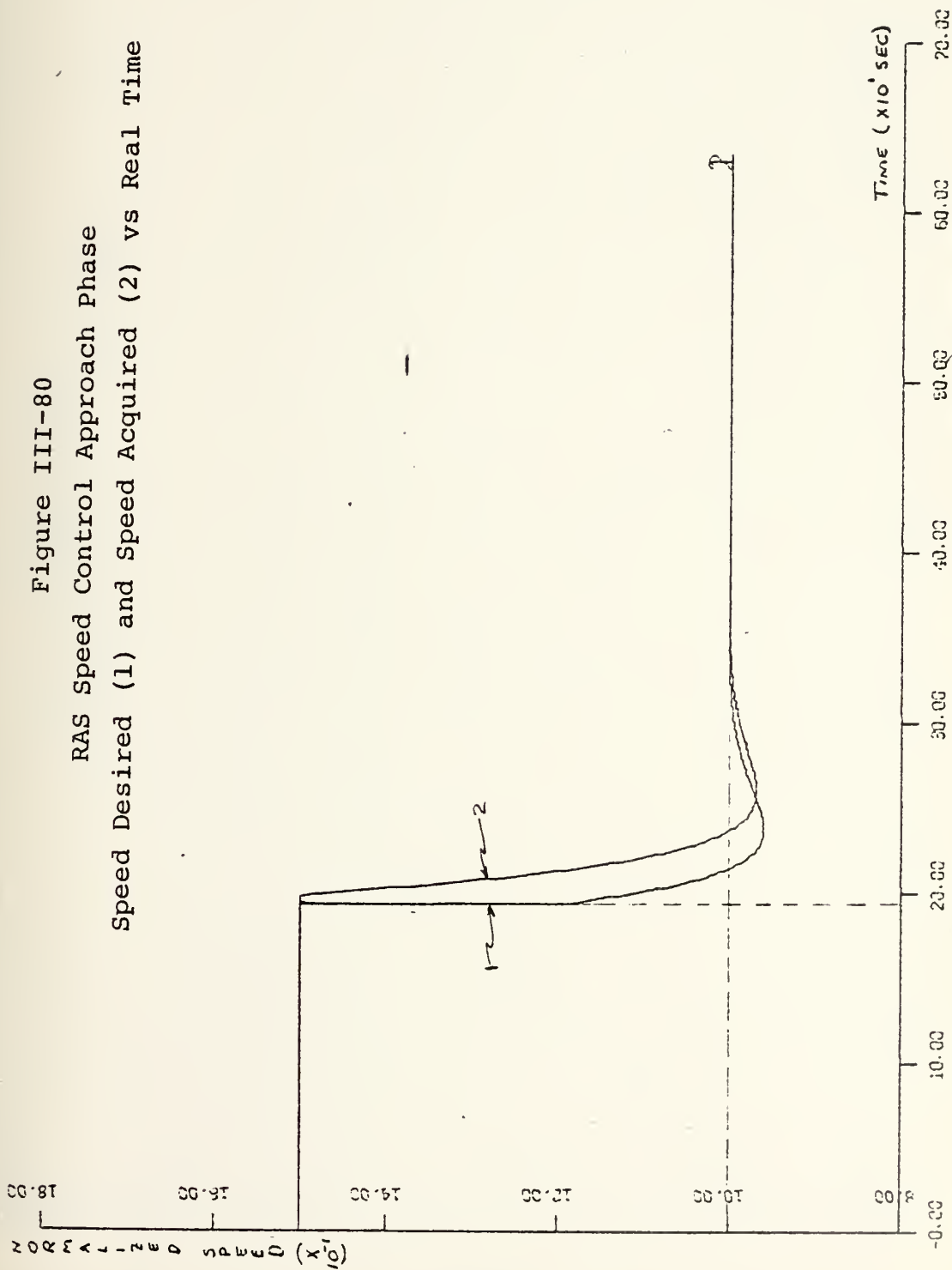


Figure III-81  
 RAS Speed Control Approach Phase  
 Position Attainment vs Real Time

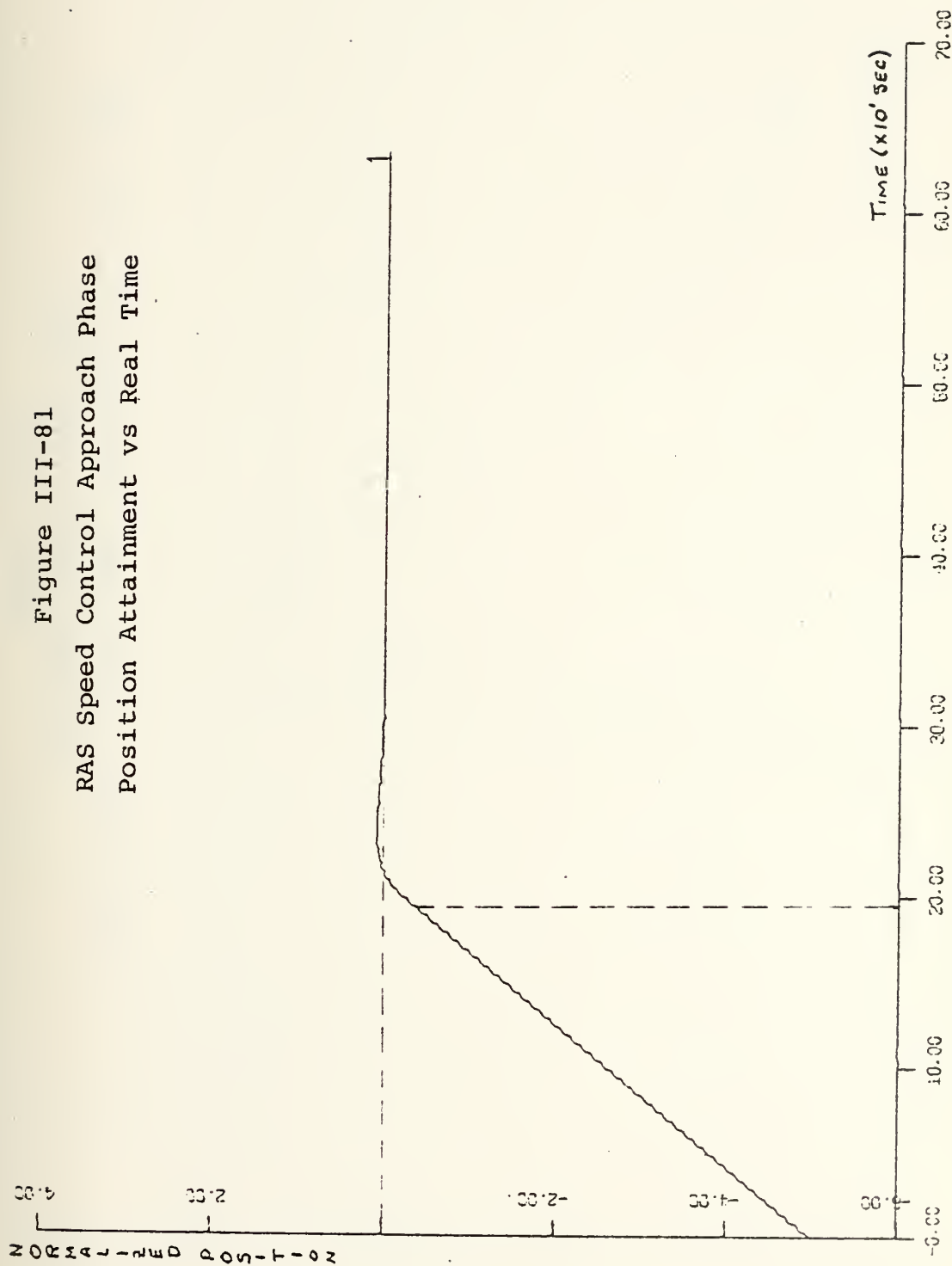


Figure III-82  
 RAS Speed Control Turn Phase  
 Speed Desired (1) and Speed Acquired (2) vs Real Time

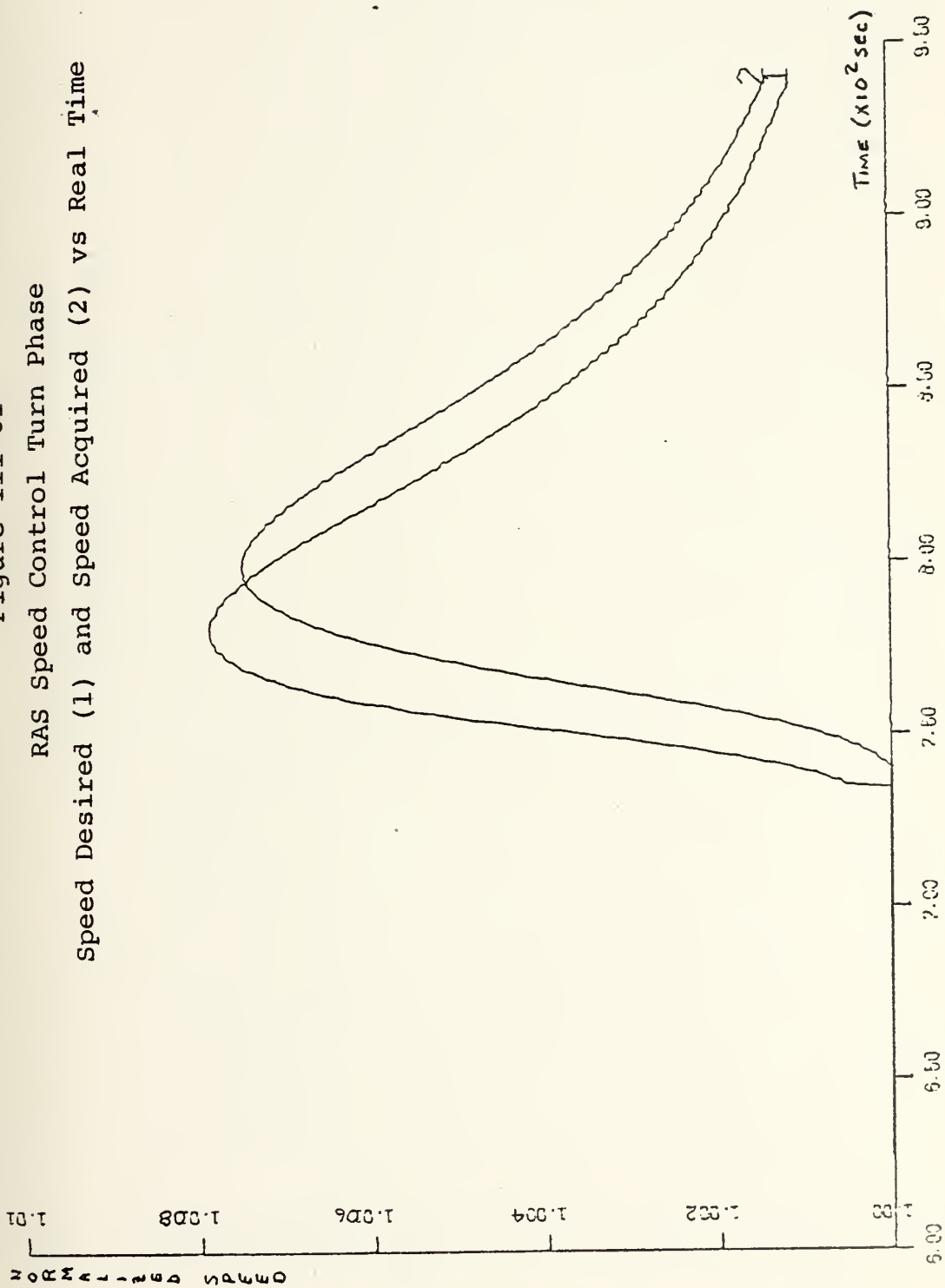
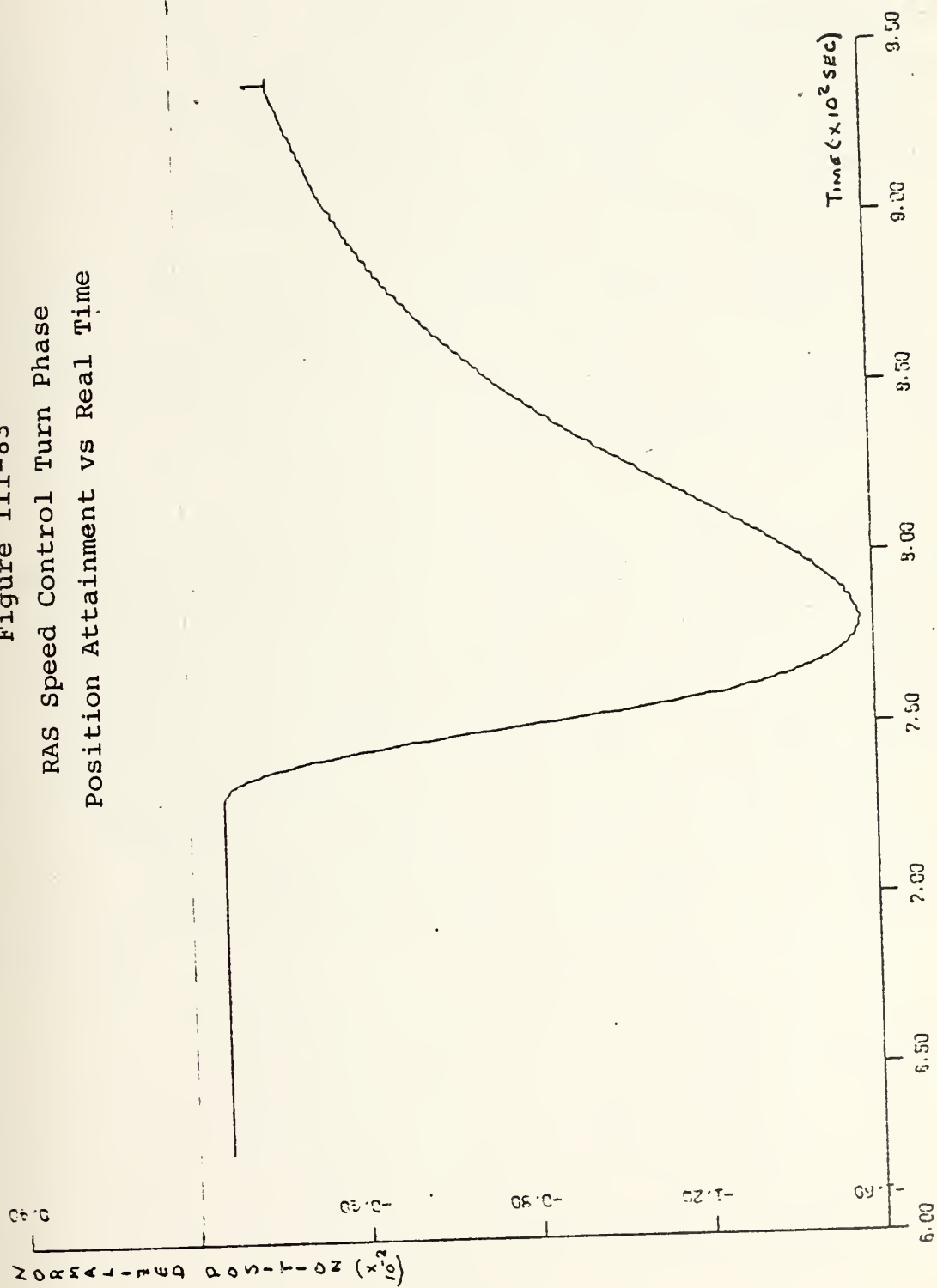


Figure III-83  
 RAS Speed Control Turn Phase  
 Position Attainment vs Real Time



```
SPIDES = SPDREC (ADX,SPDO1,SPDO2,SW)
CDCT2 = INTGRL(U02,SPDERR*LUC)
```

These equations are introduced in computer program #8 to produce figures III-80 thru III-83.

Further system study indicates that the reference ship speed must be known to a fairly high degree of accuracy. Without apriori knowlege of the reference ship speed, a constant bias is introduced. The amount of bias allowable defines the permissible uncertainty in the reference ship's initial speed. This bias can amount to as much as 0.1 ship lengths (84.48 feet) for a reference speed inaccuracy of 2.5 kncts (0.1 normalized speed). However, it is felt that the reference speed in any practical situation will initially be known to within 0.5 knots (0.02 normalized speed). This more practical error will introduce a bias of only 16 feet.

Other feedback parameters can be used to offset the lack of apriori knowlege of the reference ship speed. Since the reference ship is tracked with a high accuracy range and bearing device and the controlled ship's speed is measured, a decoupled multivariable scheme is used to further refine the reference ship speed. With high resolution devices presently available[14], it is estimated that this can be done practically to within 0.05 knots (0.002 normalized speed). This would bring the offset bias to 1.6 feet; well within previously defined errors introduced by integration step size.

#### 4. Longitudinal Position Offset

Throughout the development of the heading control and speed control, the scenario has followed the condition that the final position would be longitudinally alongside. Although this is a good assumption for ships of the same type, it does not account for RAS station differences for different ship types. To alleviate this disparity, function SPDREC was redesigned to allow pre-planned offset condition to exist. Function SPDOFC of appendix A is a result of this redesign.

Simulation runs, with a change of the speed control function only, resulted in some unstable conditions existing in the heading control loop. The cause of this phenomenon stems back to the adaptive gain scheme used and the changes made to force the control loop to a steady state value prior to a turn. By using a favorite ploy of experienced conning officers, this problem is alleviated. The ploy is to take the ship alongside and then either drop back to station or surge forward to station. This method is accomplished by setting the initial offset (XOPS) to 0.0. The final desired offset (XOFSD) is stored and not used until the ship is settled out alongside. It is subsequently used as shown in the following Fortran code:

```
IF (ATIME.GT.450.0) XOPS = XOFSD
```

This method solved the gain transition problem. It did not, however, give a completely stable simulation run. Unstable conditions still existed at the end of the turn phase. This is not surprising, considering the heading control optimization method used. The set of gains previously found were for the alongside scenario only.

Different interactive forces and moments at the offset position cause these gains to be no longer optimal.

By relaxing the control loop in the heading velocity feedback gain (VFBG), sub-optimal control at all practical offset positions is achieved. The gain VFBG was changed from 0.084028 to 0.1 in the turn phase adaptive gain schedule without significant loss of control efficiency for alongside operation (2.3 feet maximum excursion vice 2.0 feet previously obtained). Subroutine SWTCHF of appendix A reflects the gain change and offset calculations required. Computer program #9 incorporates the changes required for offset simulation. Table III-6 is a cross reference listing of the plots obtained. From these figures, the effect of different longitudinal positions is readily apparent. An offset of 0.1, equating to 52.8 feet, causes greater lateral excursions when astern (XOFSD = -0.1) of the alongside position than when ahead (XOFSD = 0.1). The longitudinal position maintainment, however, is essentially the same in all cases.

Run	Approach Phase Plots			Turn Phase Plots		
	A	B	C	A	B	C
XOFSD	0.0	0.1	-0.1	0.0	0.1	-0.1
Lateral Distance DY	84	86	90	94	96	99
Yaw Difference	85	87	91	95	97	100
Speed Response	80*	88	92	82*	82*	82*
Longitudinal Position DX	81*	89	93	83*	98	101

\* Note: These plots are the same as those obtained from computer program #8 and are not repeated here.

Table III-6  
Position Offset Testing Cross Reference

An alternative to the method shown here is again a completely adaptive gain scheme which would achieve optimal control instead of the sub-optimal control settled for here. The alternative may become even more important if the nonlinear terms of the equations of motion are considered. This would couple the heading and speed control designs to a larger extent than encountered in the interactive forces and moments.

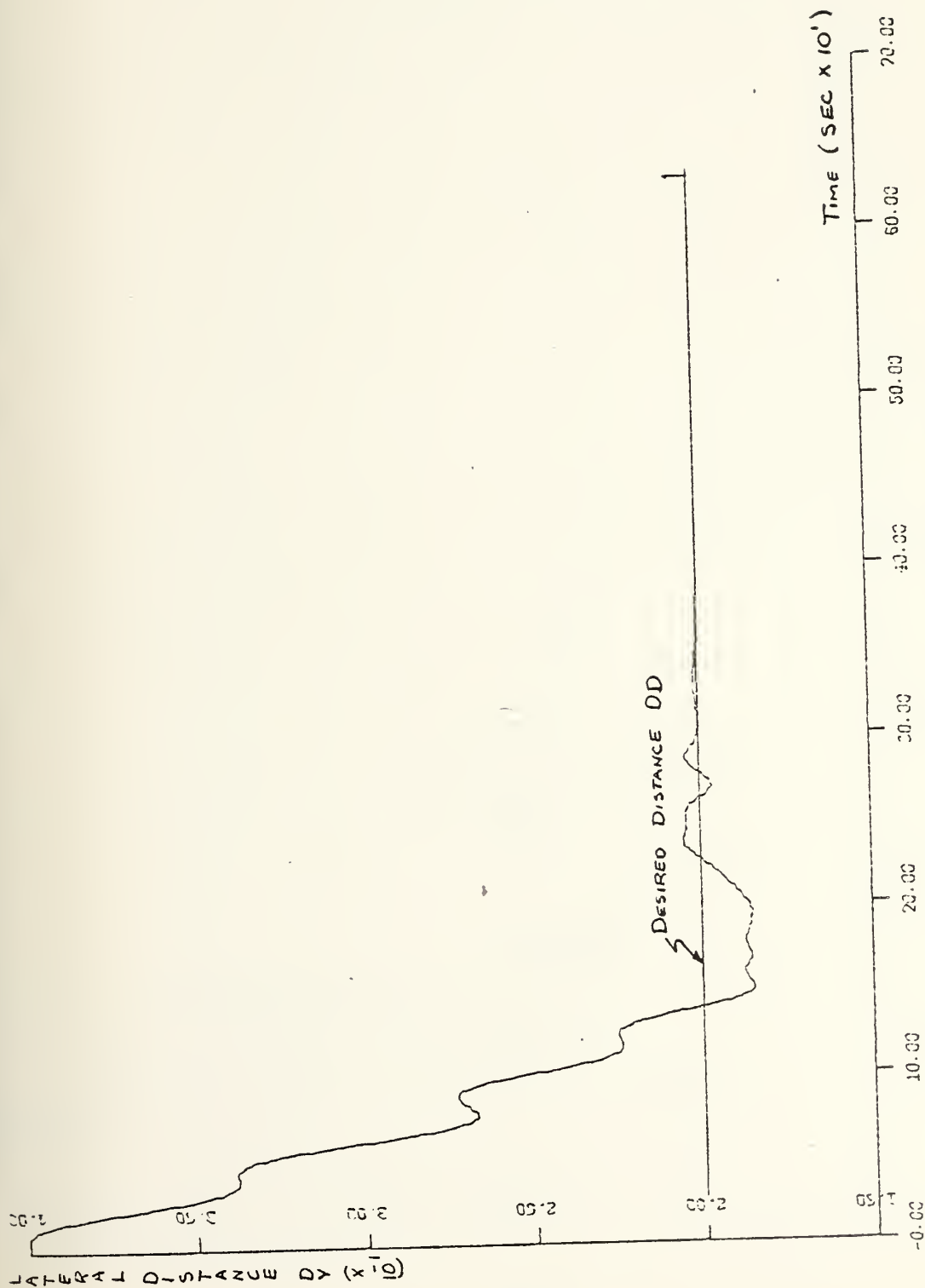


Figure III-84  
Approach Phase Run A Lateral Distance DY

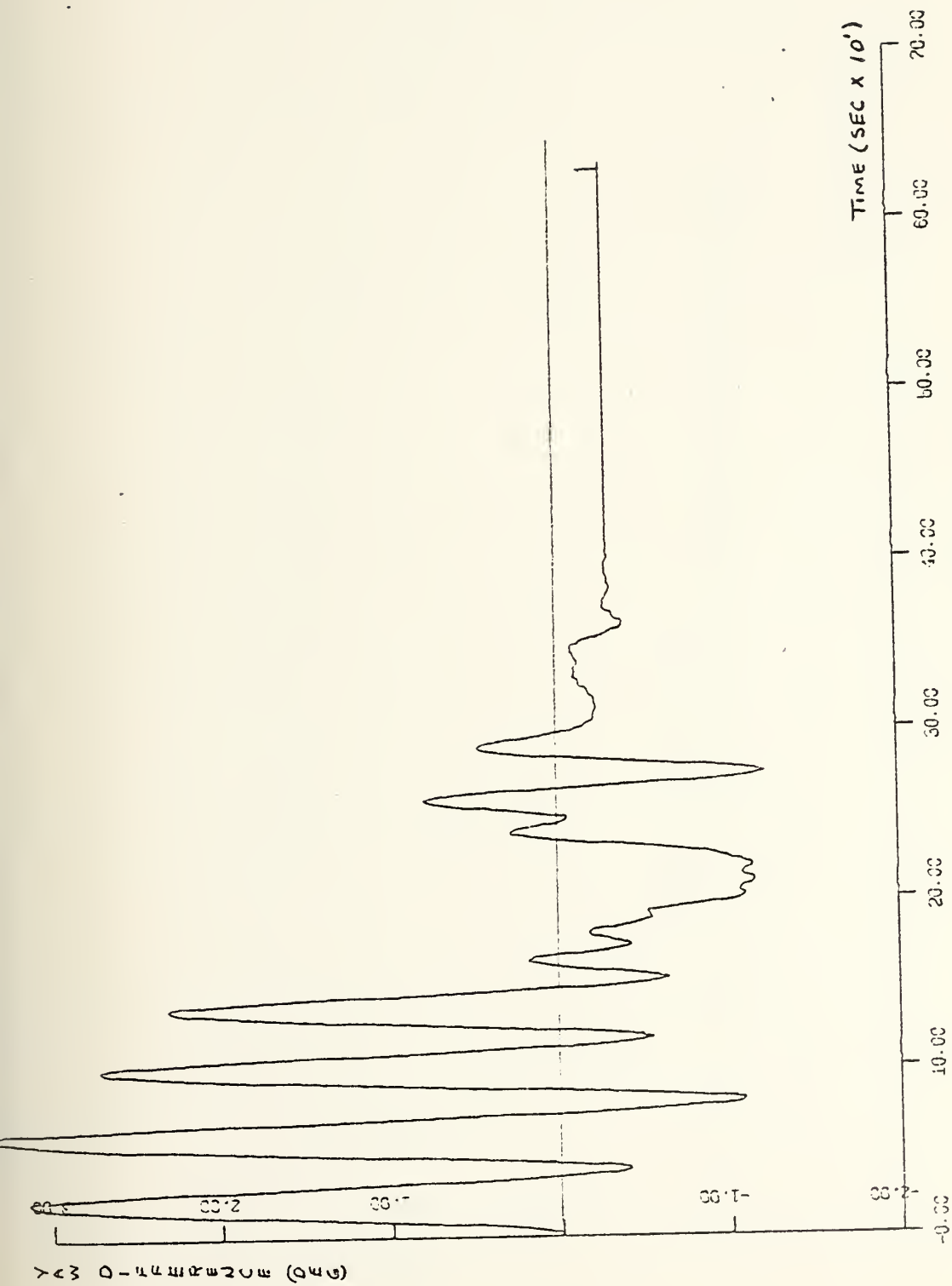


Figure III-85  
Approach Phase Run A Yaw Difference

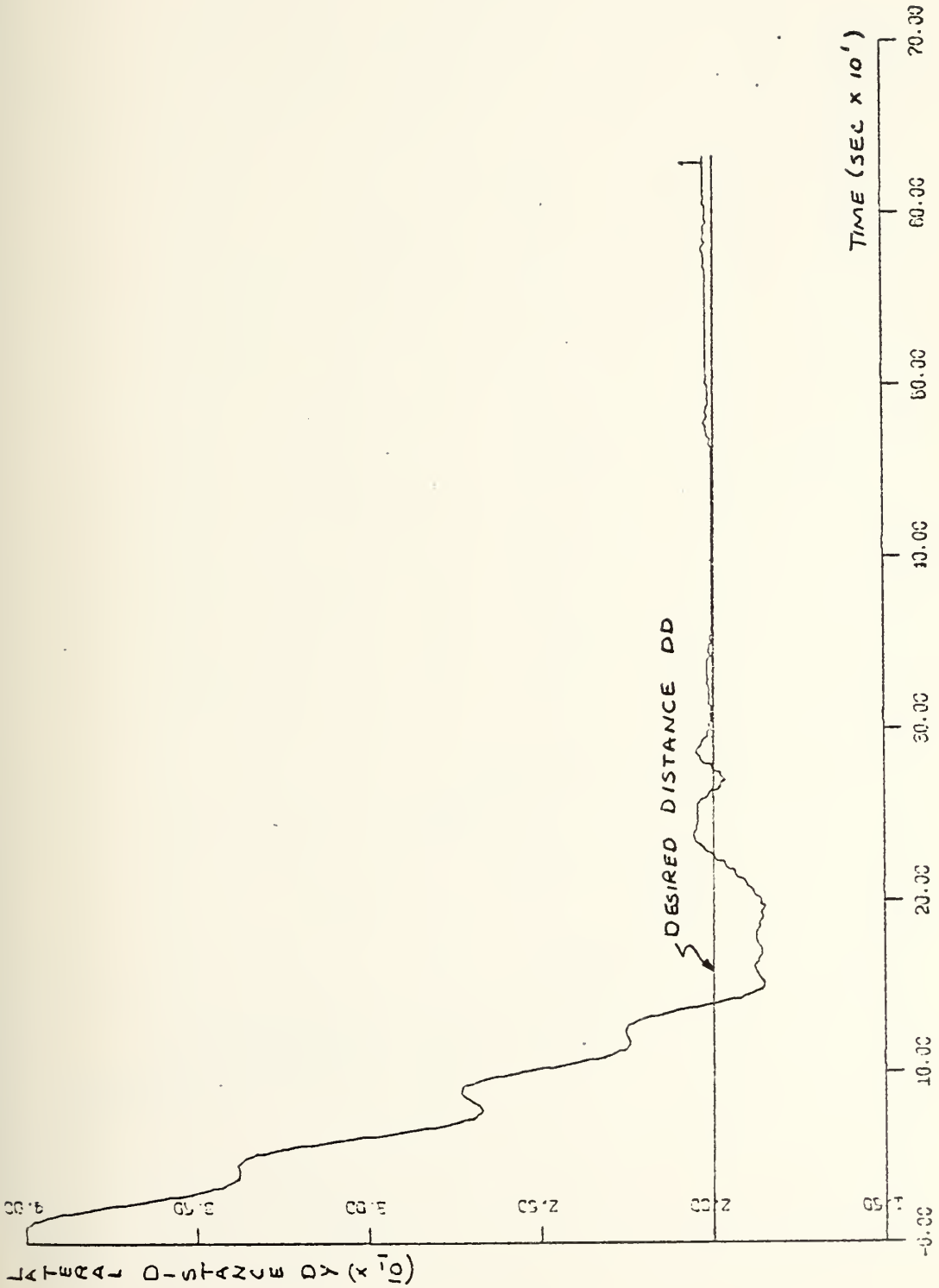


Figure III-86  
Approach Phase Run B Lateral Distance DY

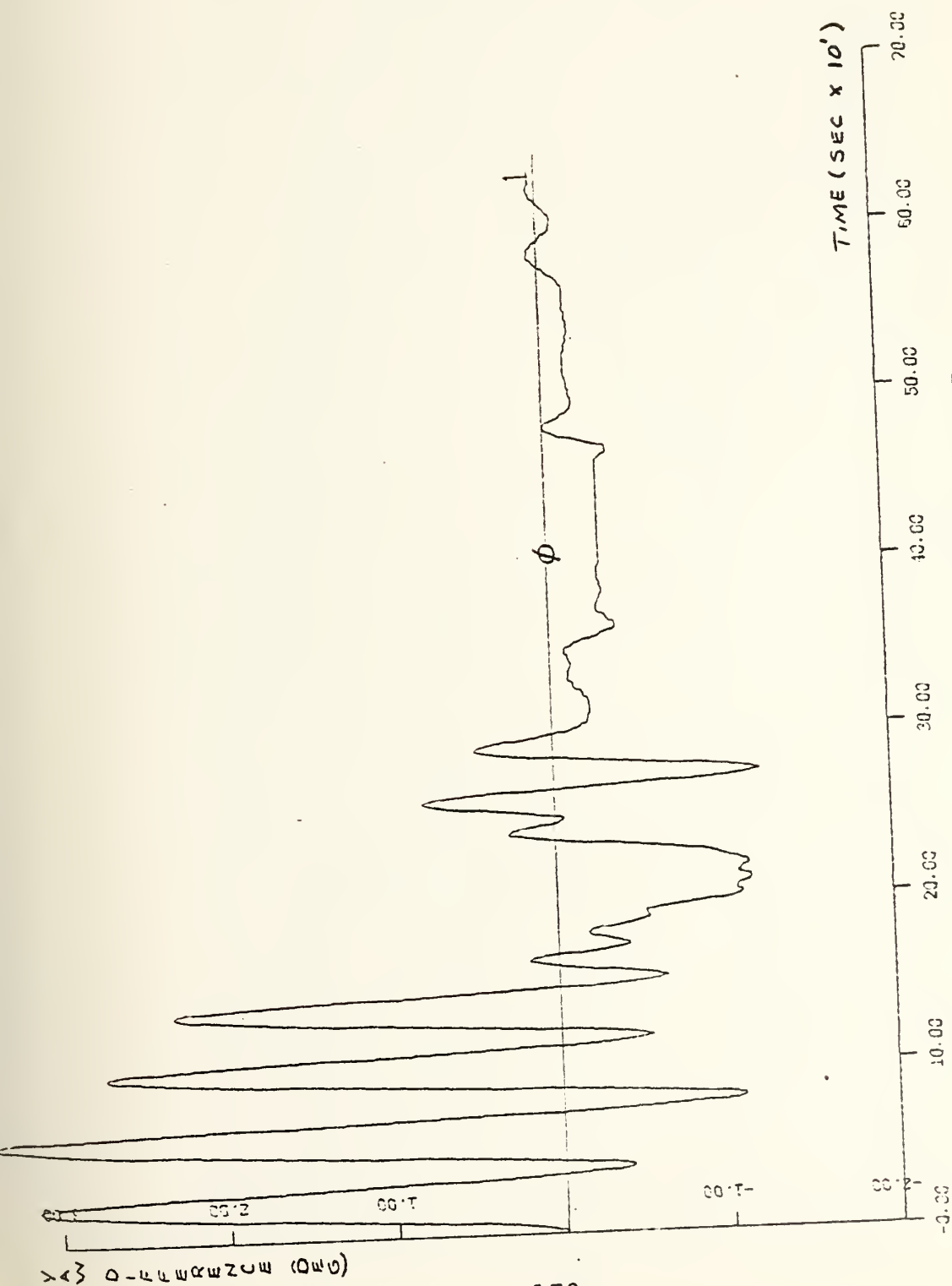


Figure III-87  
Approach Phase Run B Yaw Difference

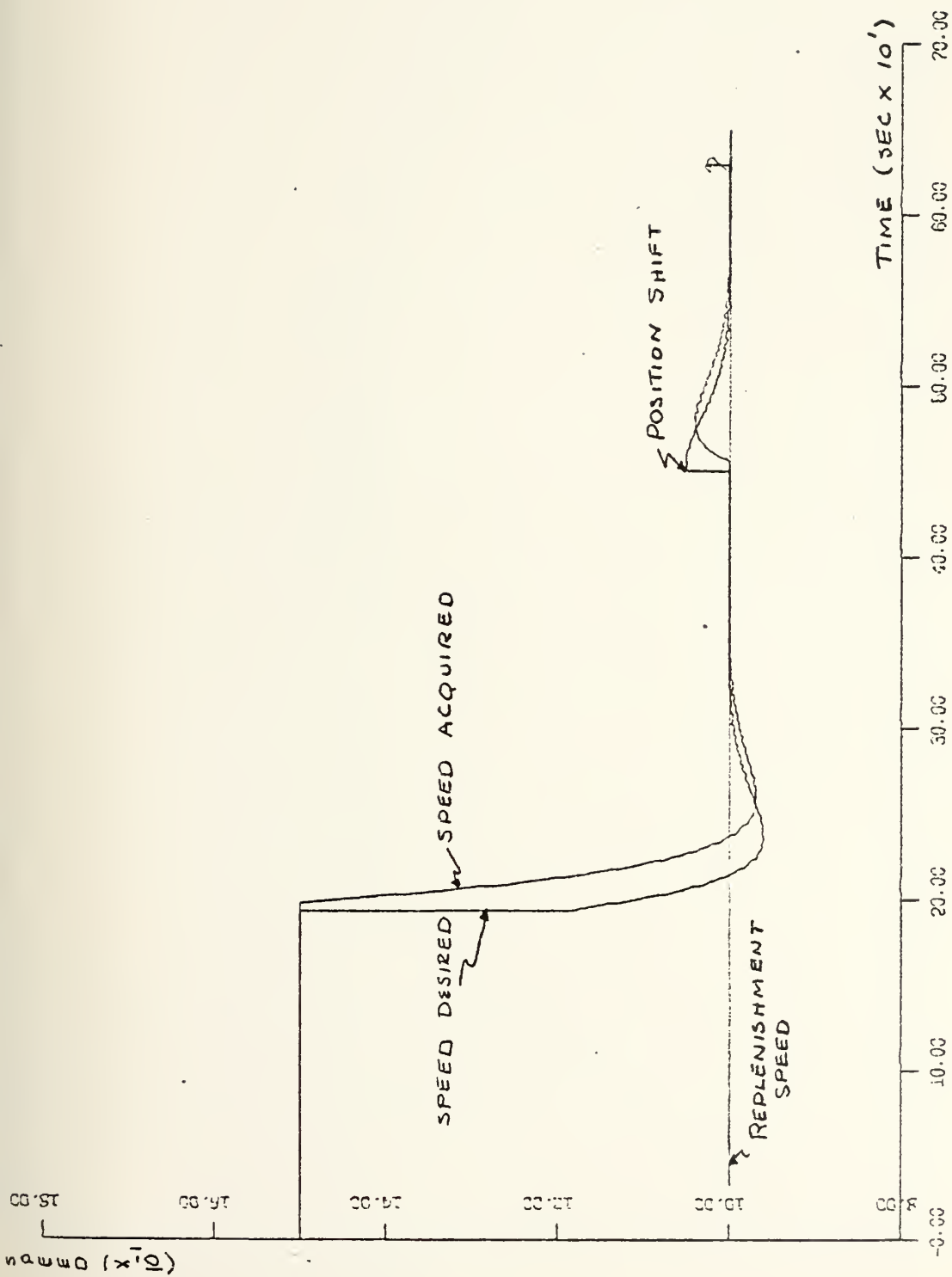


Figure III-88  
Approach Phase Run B Speed Response

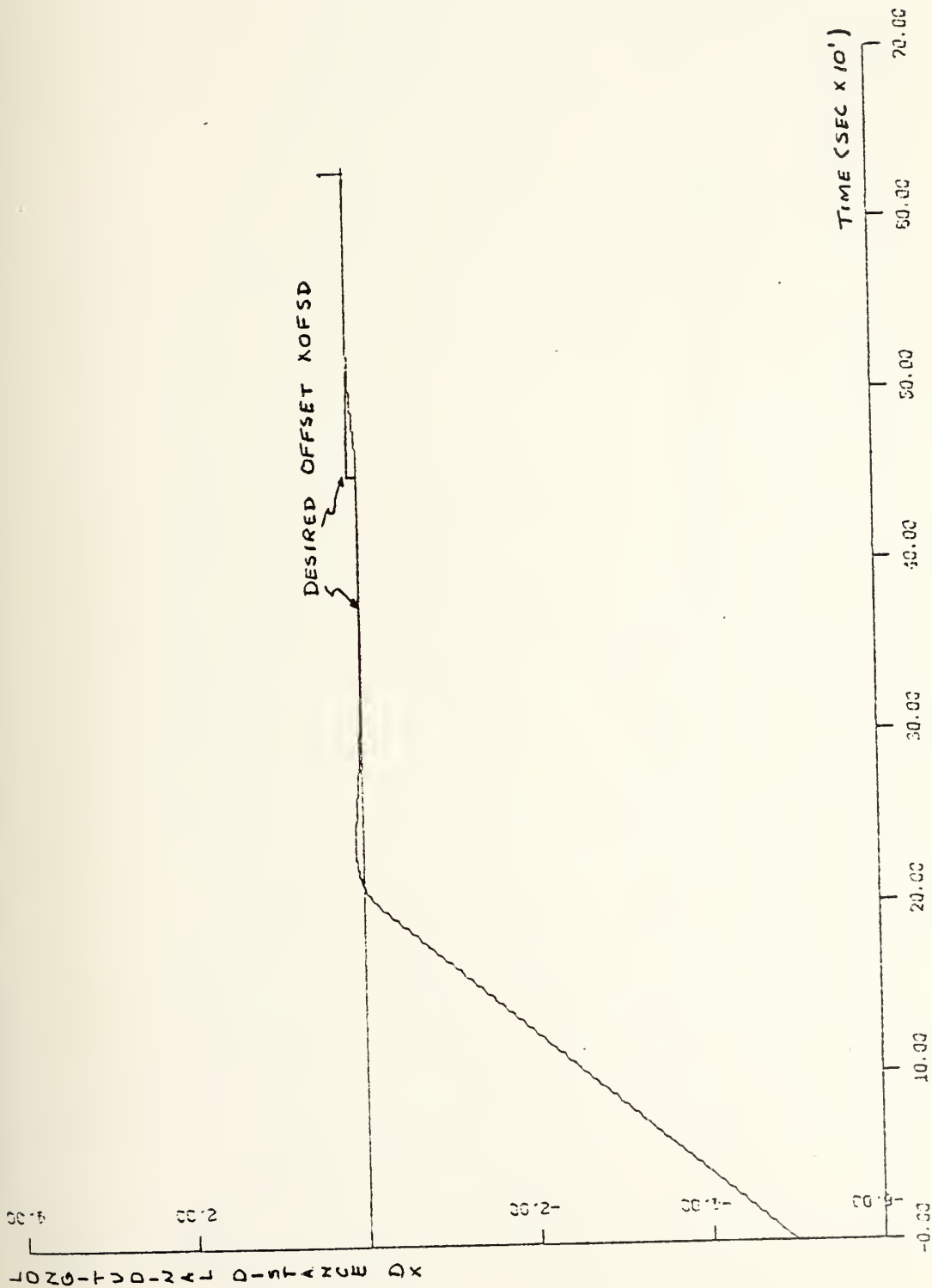


Figure III-89  
Approach Phase Run B Longitudinal Position DX

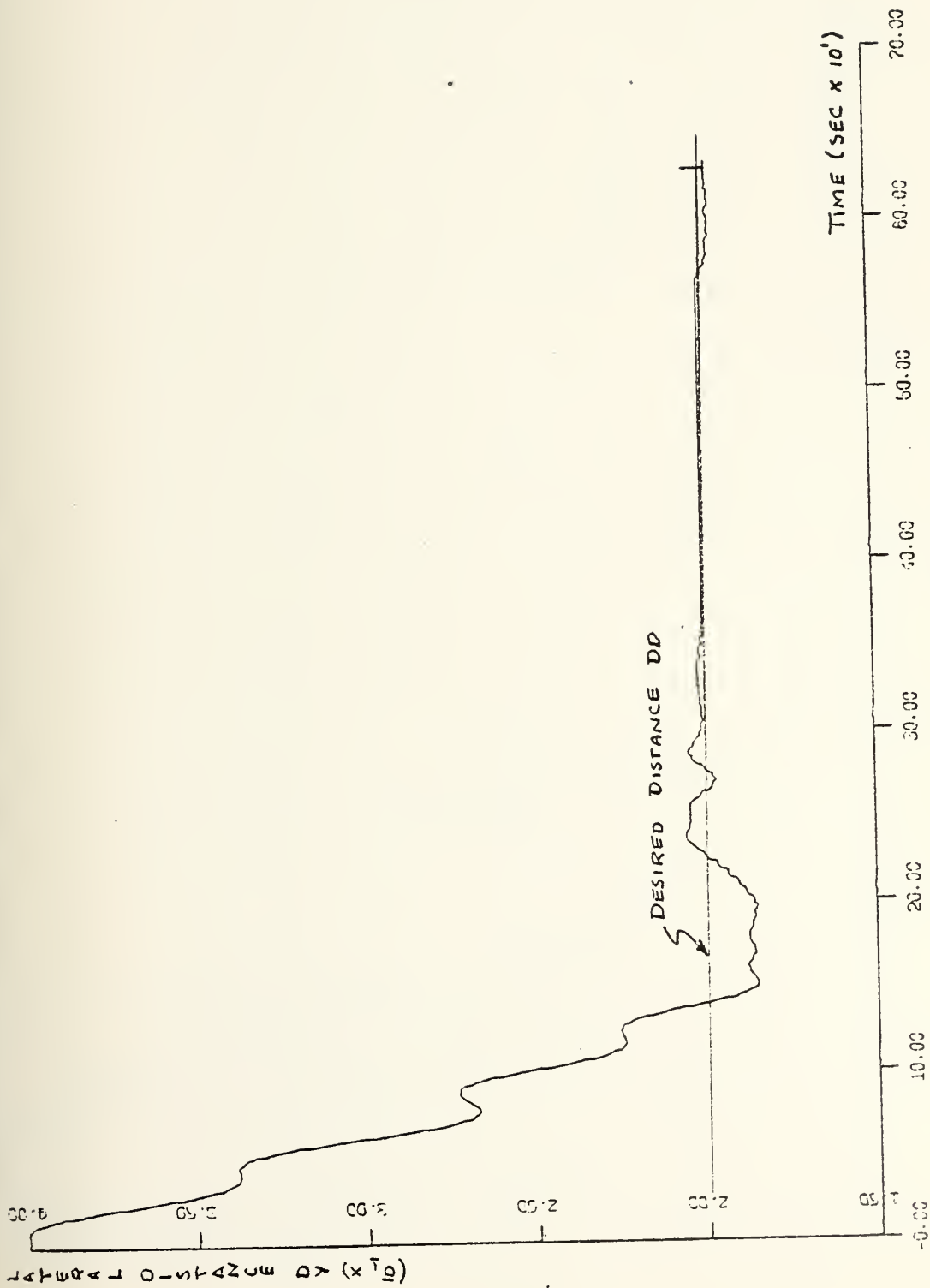


Figure III-90  
Approach Phase Run C Lateral Distance DY

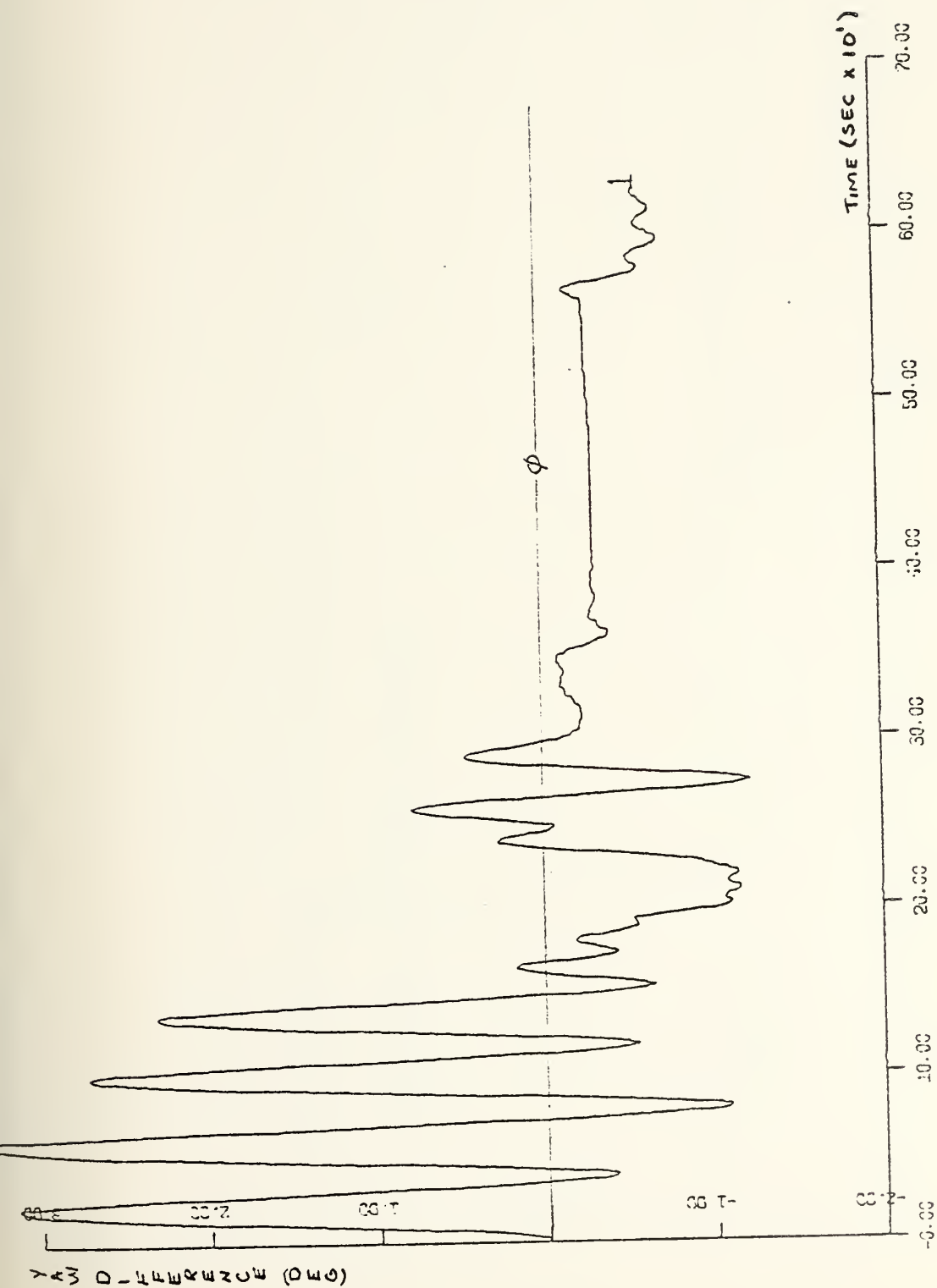


Figure III-91  
Approach Phase Run C Yaw Difference

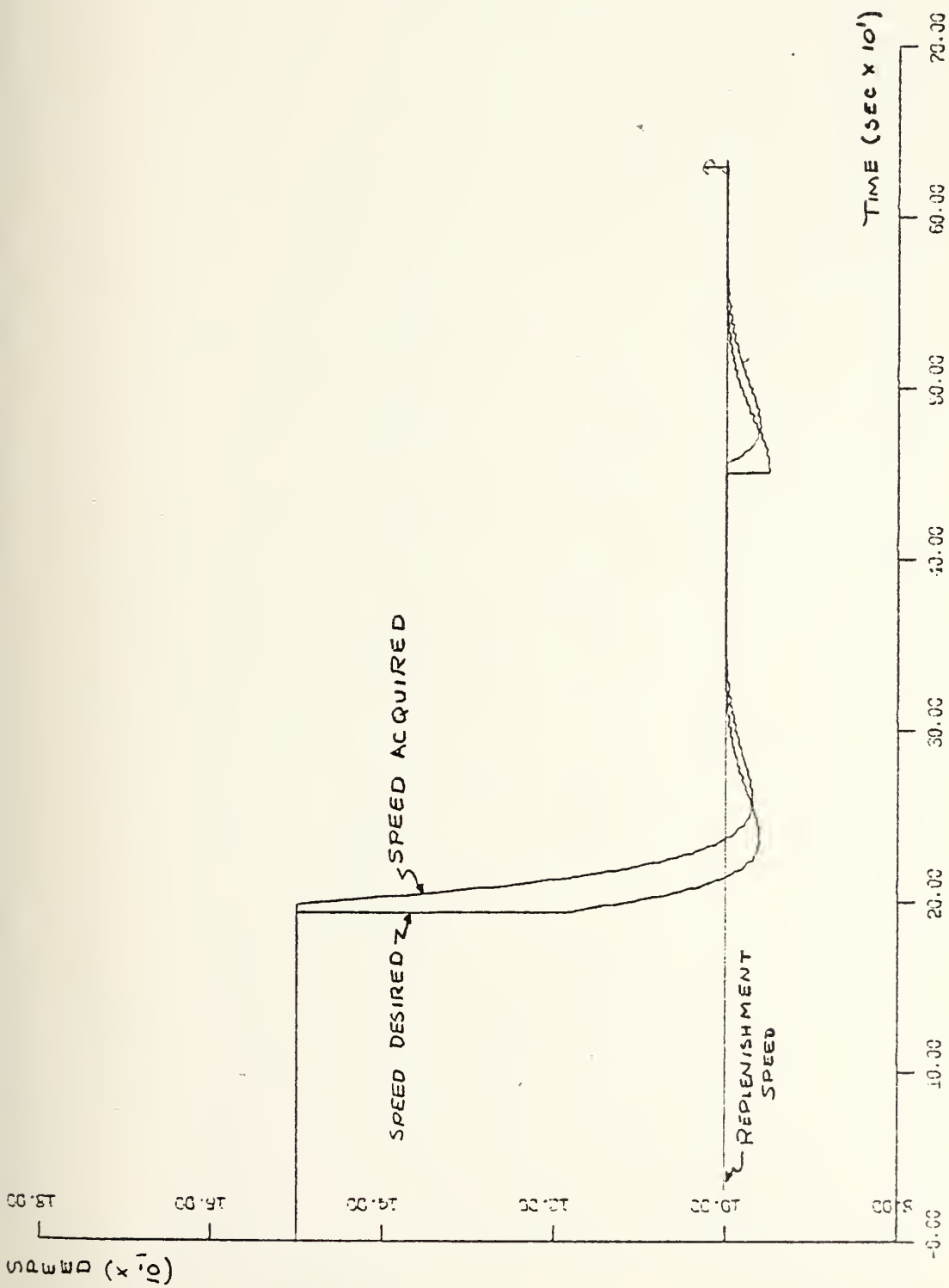


Figure III-92  
Approach Phase Run C Speed Response

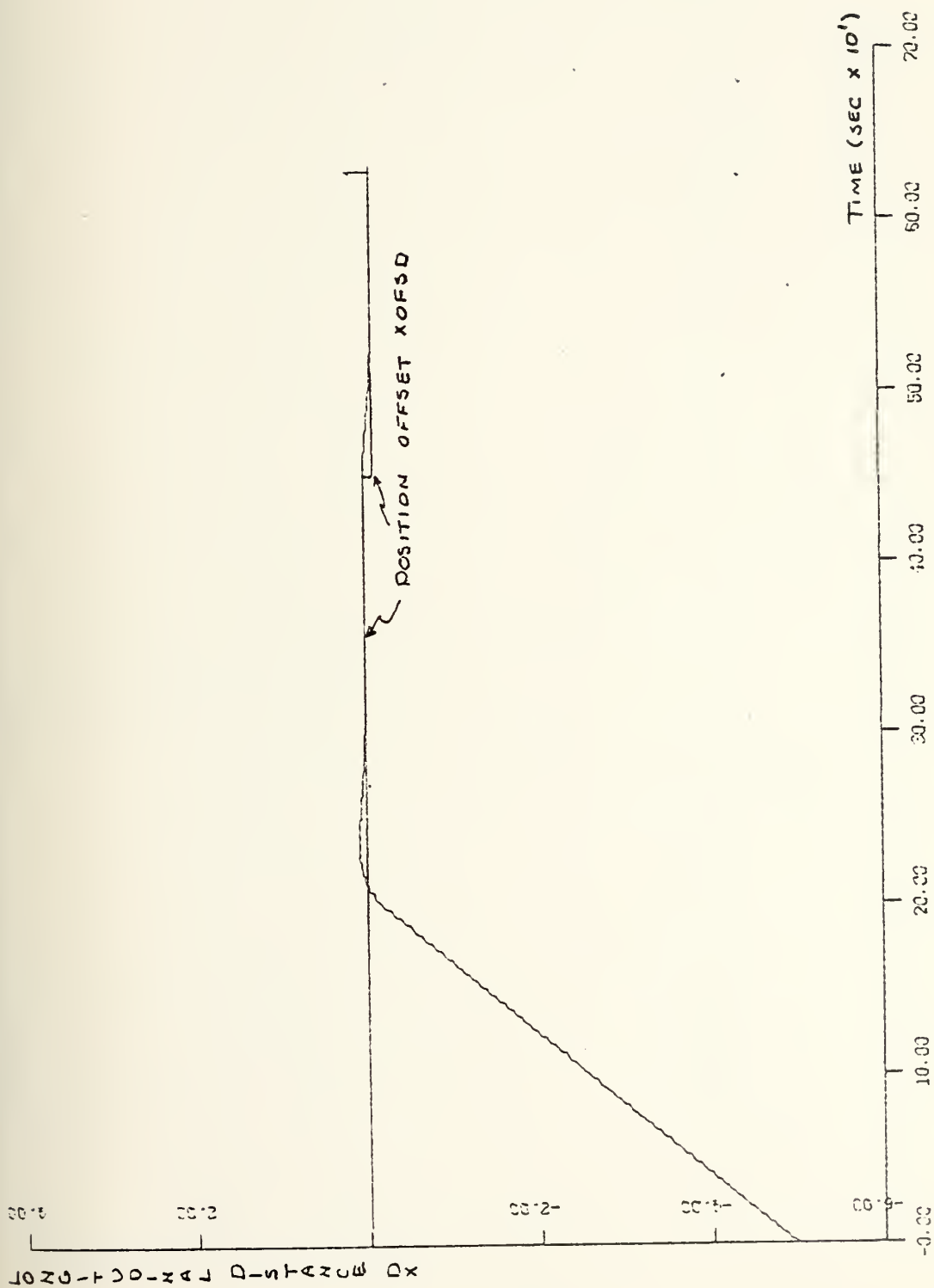


Figure III-93  
Approach Phase Run C Longitudinal Position DX

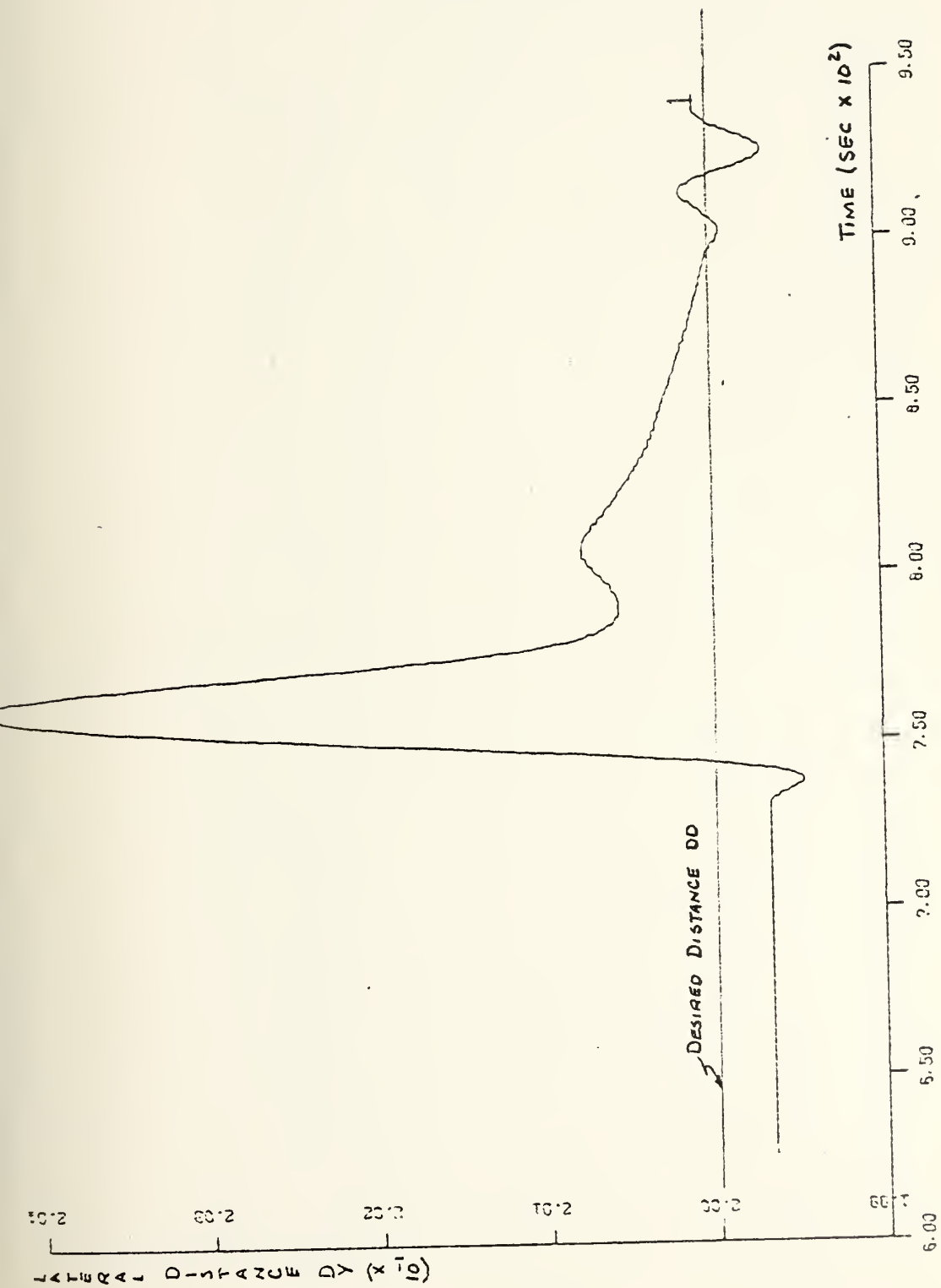
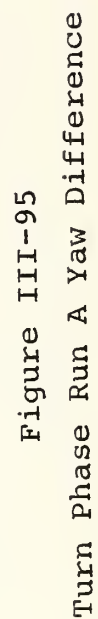


Figure III-94  
Turn Phase Run A Lateral Distance DY



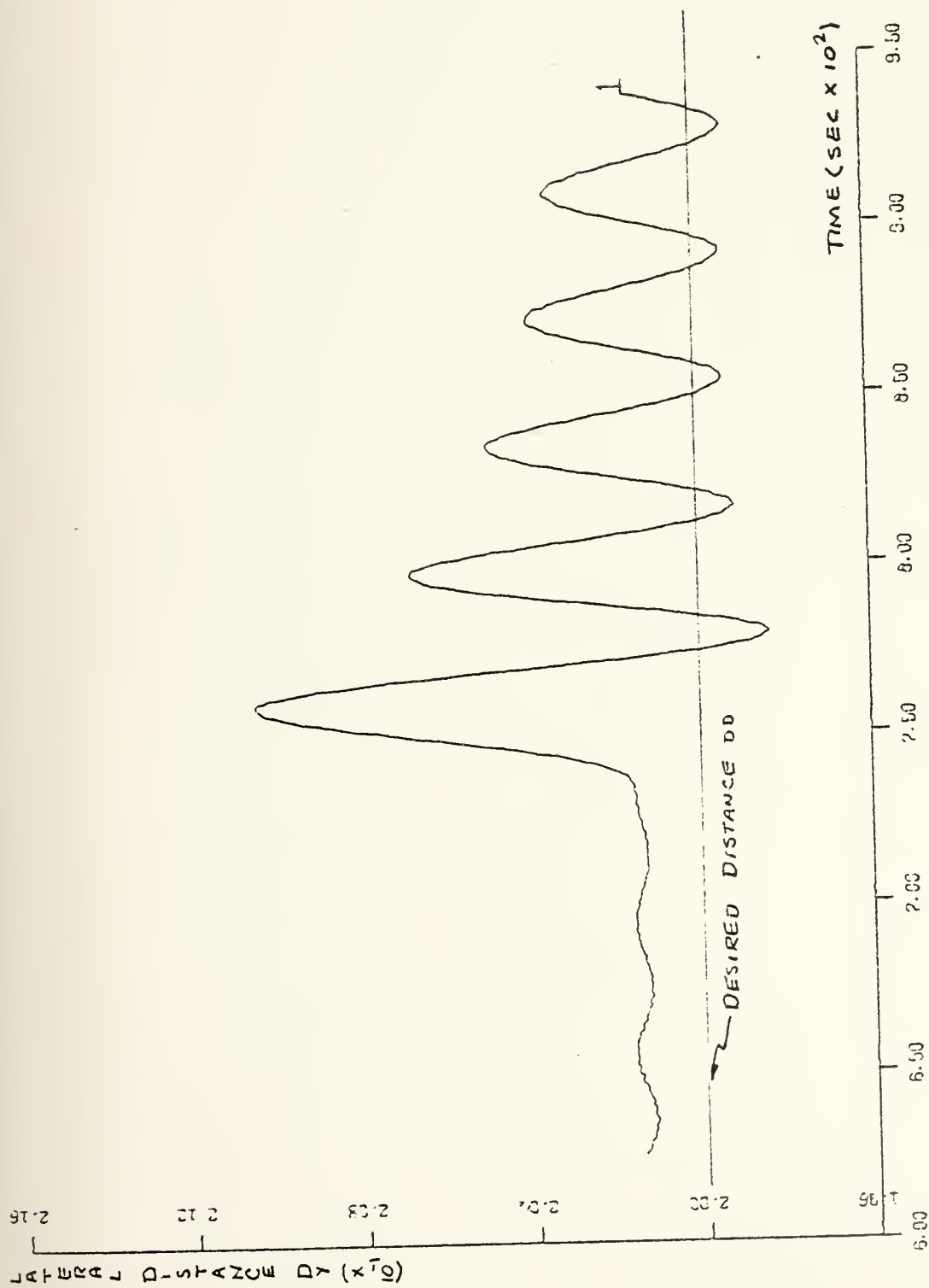


Figure III-96  
Turn Phase Run B Lateral Distance DY

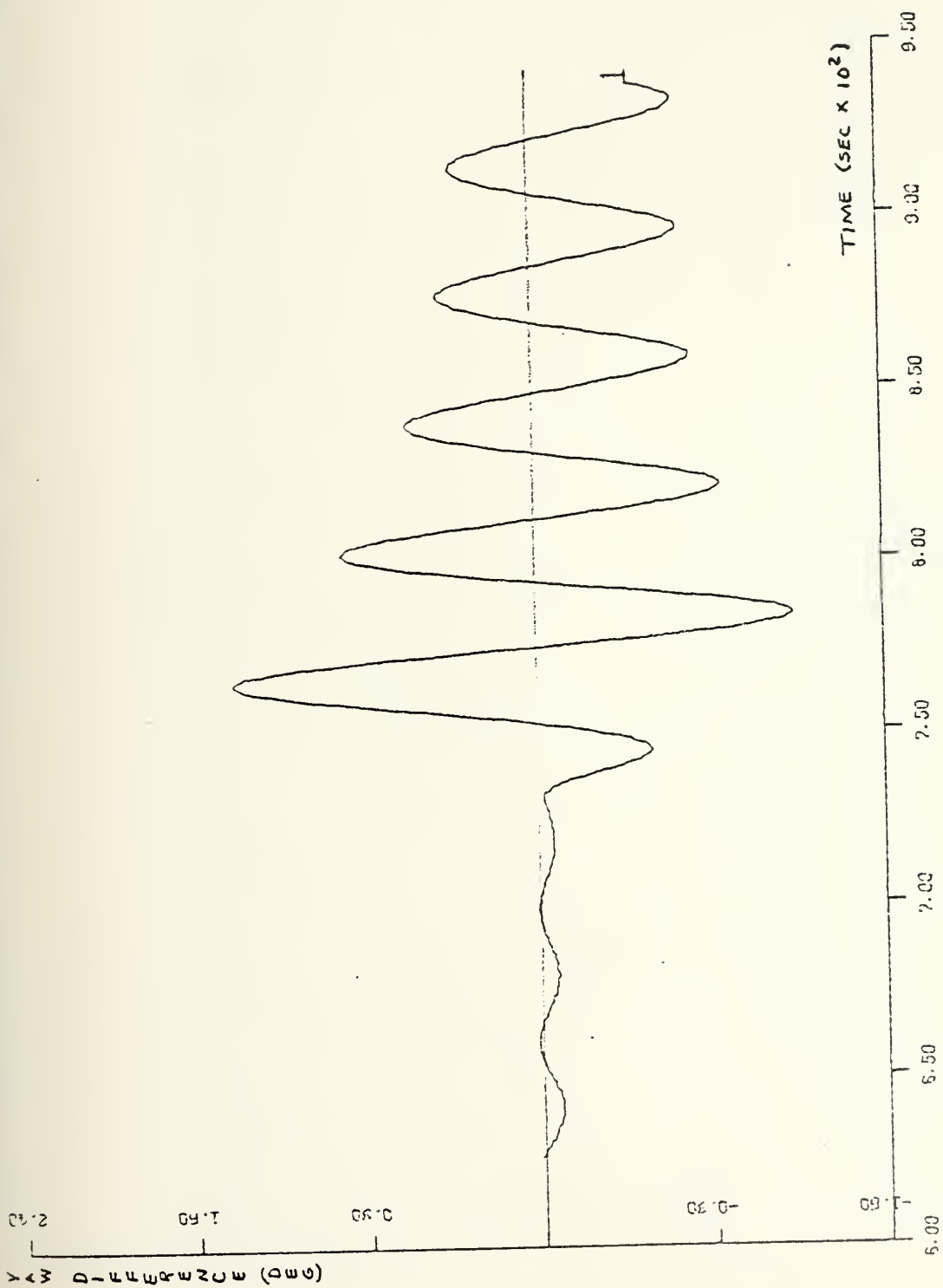


Figure III-97  
Turn Phase Run B Yaw Difference

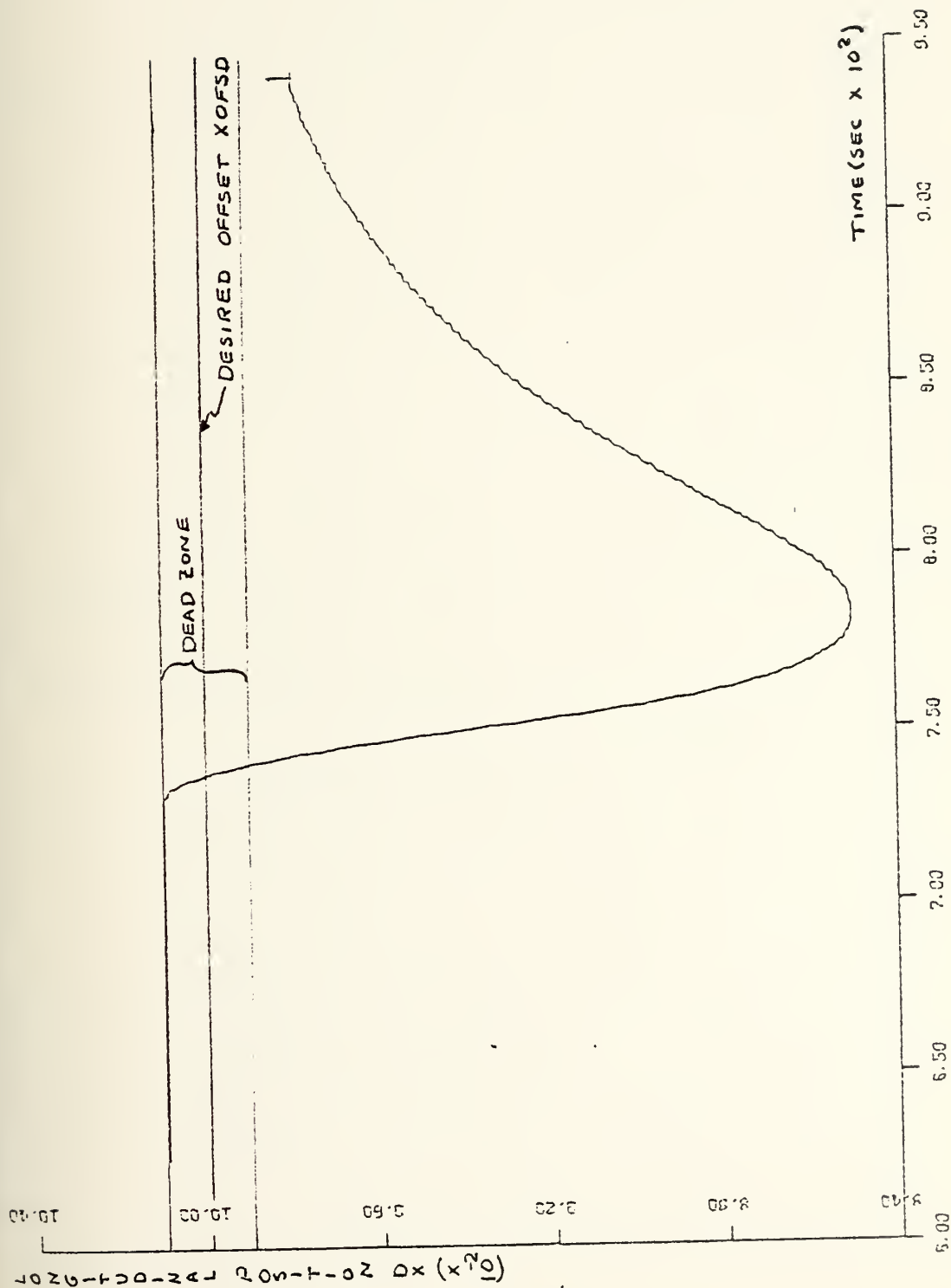


Figure III-98

Turn Phase Run B Longitudinal Position DX

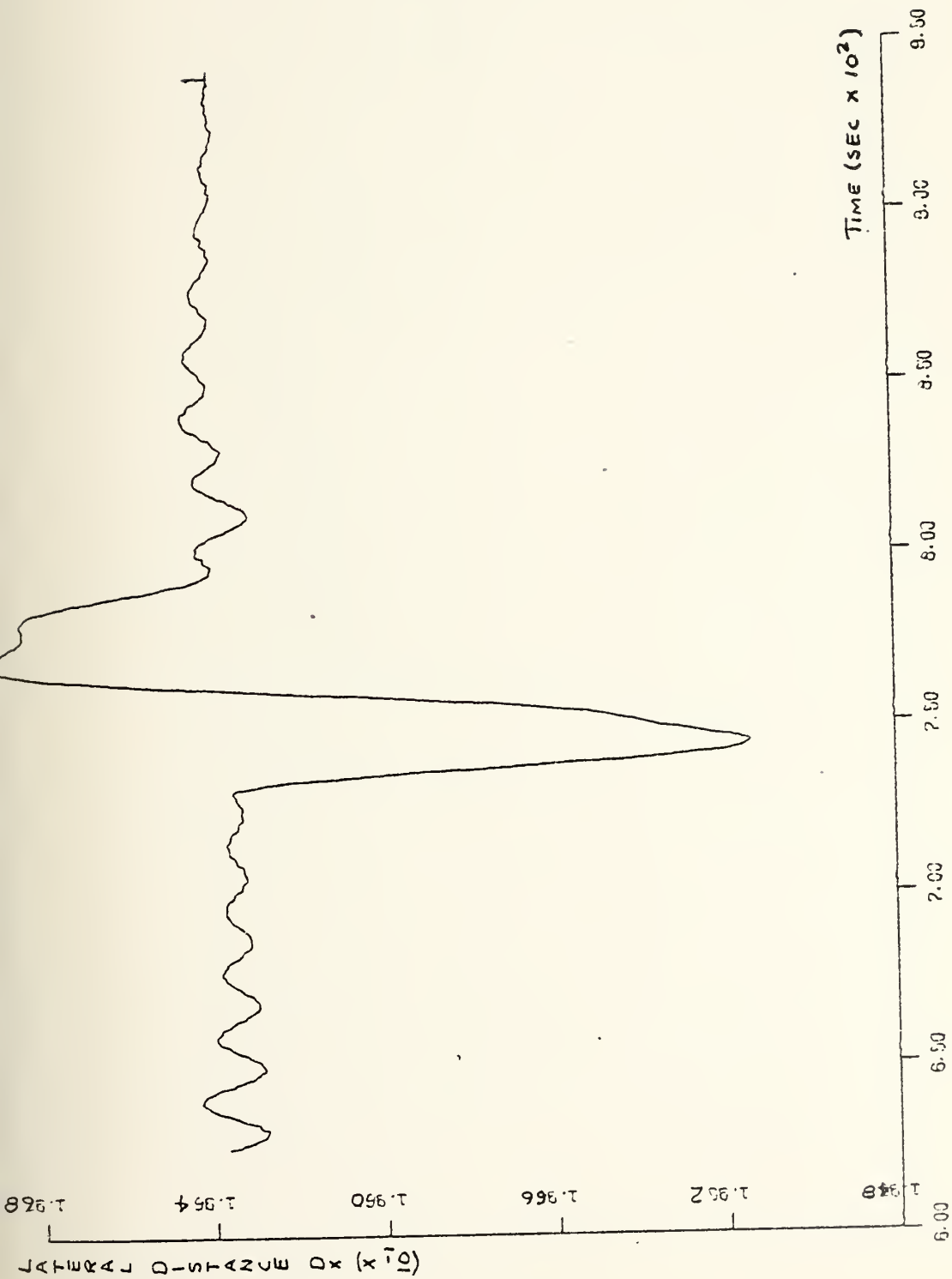


Figure III-99  
Turn Phase Run C Lateral Distance DY

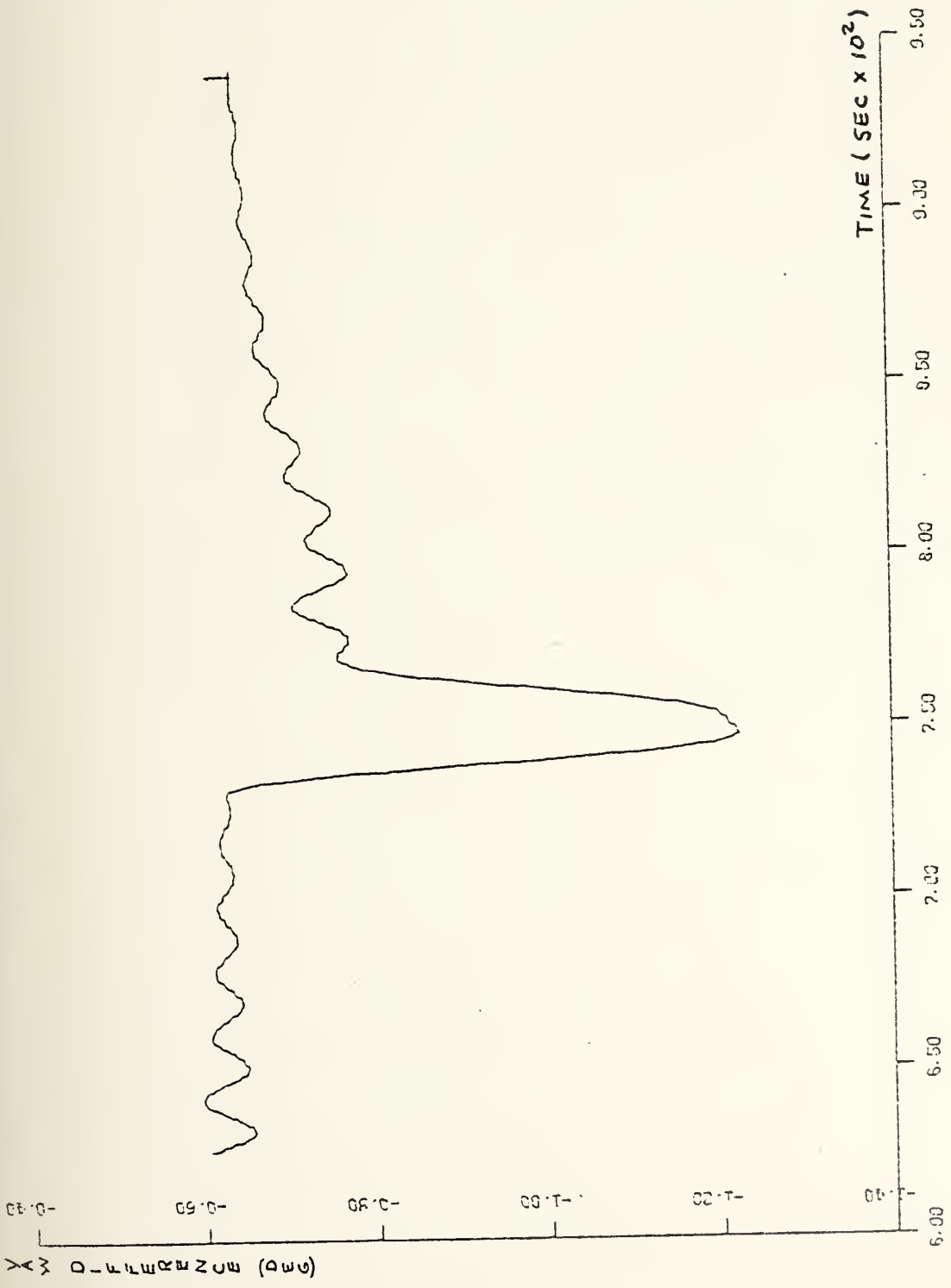


Figure III-100  
Turn Phase Run C Yaw Difference

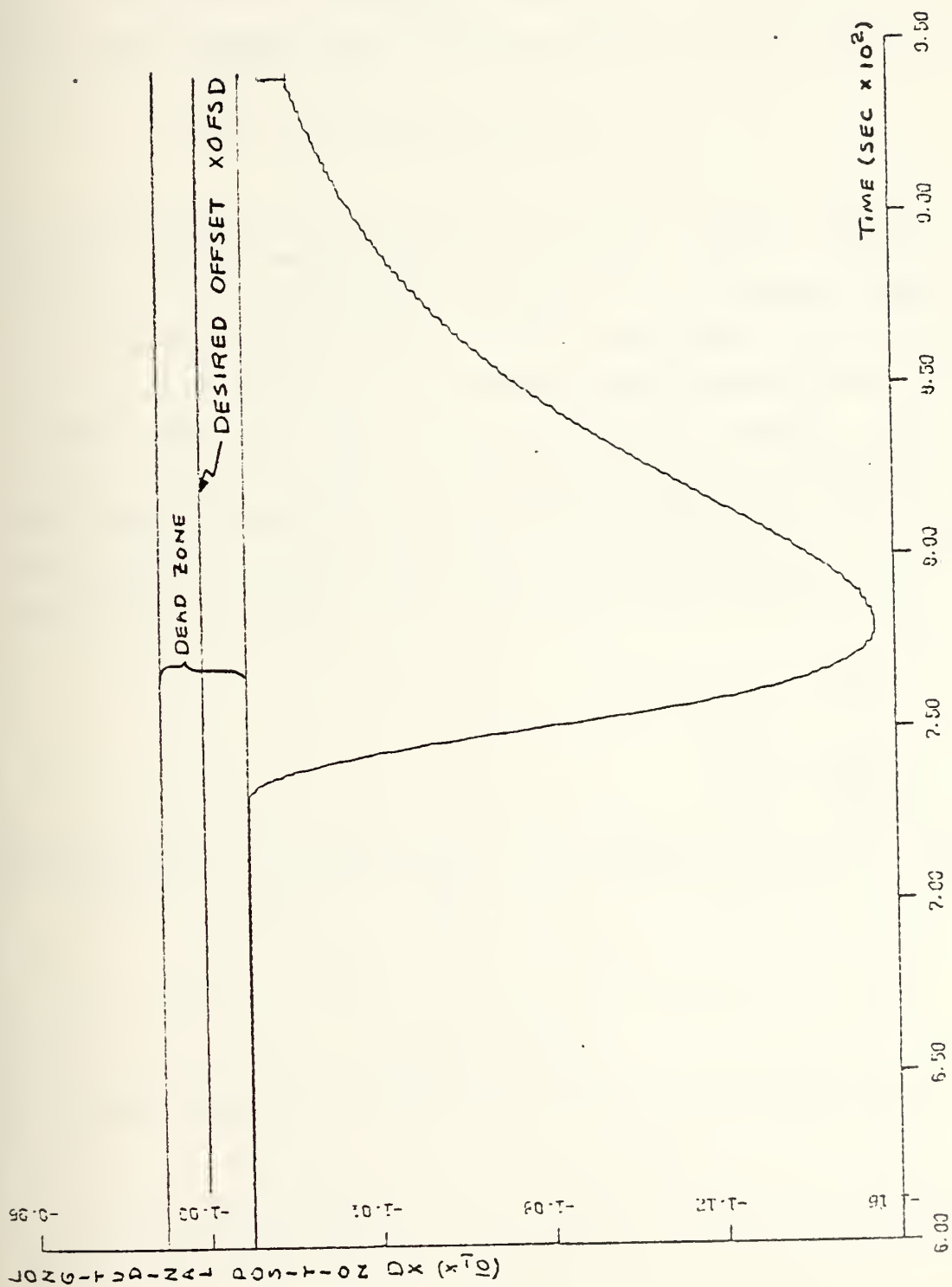


Figure III-101  
Turn Phase Run C Longitudinal Position DX

## 5. Wave Effects on Velocity Control

The final testing procedure involves validation of the speed control system in the presence of waves. This perturbation testing continues that started in section A. of this chapter for heading control. In chapter II the WX force was modeled thru the intermediate force IF32 as:

$$IF32 = KC1 \cdot D2 + NC2 + KC1 \cdot WX$$

By introducing the force in this way, a severe limitation is placed on the magnitude of the force. In the mariner model used, the KC1 coefficient (XDELR) is considered negligible or, at best, only 0.00005. This translates, in the original equations of motion, to a maximum speed perturbation of only 0.0355 kts. for the wave amplitude chosen. The second drawback of this method, with even greater consequences, is that the perturbation is introduced before the control loop. Delay of the wave perturbation is produced making it out of phase with the other wave force (WY) and moment (WN).

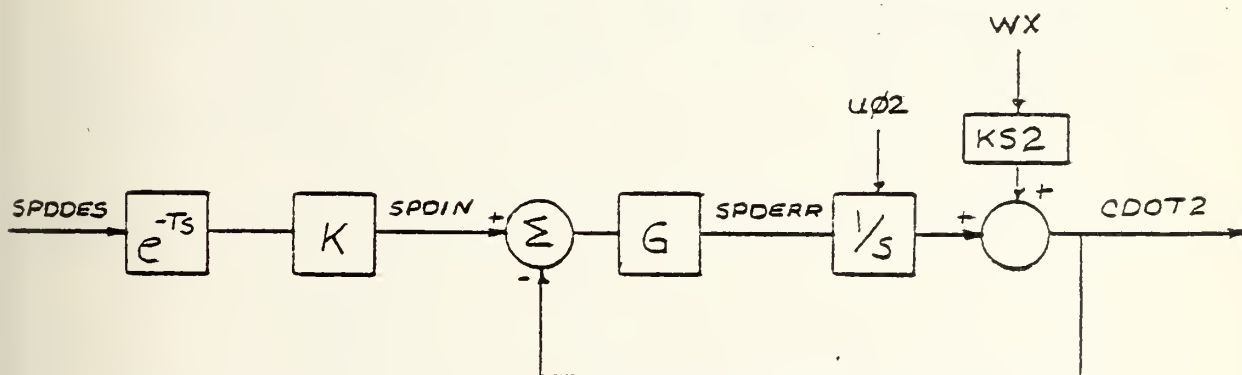


Figure III-102

Block Diagram of Wave Introduction in Speed Loop

In order to bring about uniform introduction of this wave force, its effect is inserted just past the integrator

of the speed control loop as shown in figure III-102. This is coded in the DSI simulation program as:

$$CDOT2 = INTGRL(U02, SPDERR * LUC) + KS2 * WX$$

A value of -1.0 for KS2 will give a maximum wave perturbation of 0.85275 kts. (a much more realistic perturbation for the high sea state simulated). Figure III-103 portrays the speed desired and speed acquired for the approach phase in the presence of sea state. From this it can be seen that the speed acquired is very dependent upon the sea state present. The control law, however, presents a very stable reference for the speed loop which gives an approach longitudinal position (DX) plot indistinguishable from that of figure III-81. More prominent perturbation results are evident in the turn phase plots of figures III-104 and III-105. The speed response of figure III-104 allows a maximum longitudinal position excursion of 9.5 feet (0.018 normalized position). as compared with 8.286 feet (0.0157 normalized) in calm sea.

These results show that the speed control system is very stable and corrects well for large external perturbations.

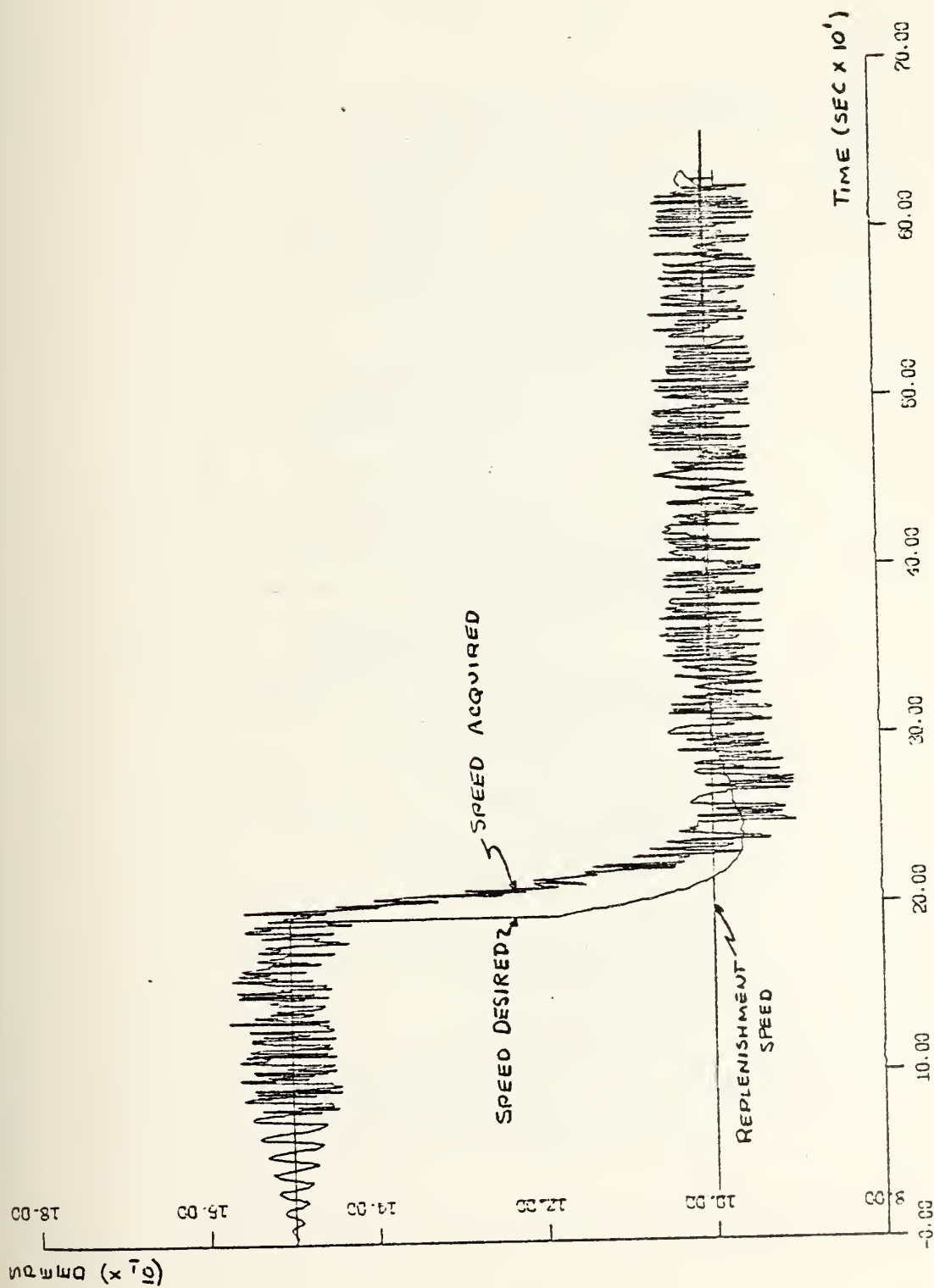


Figure III-103  
Approach Phase Speed Response in Waves

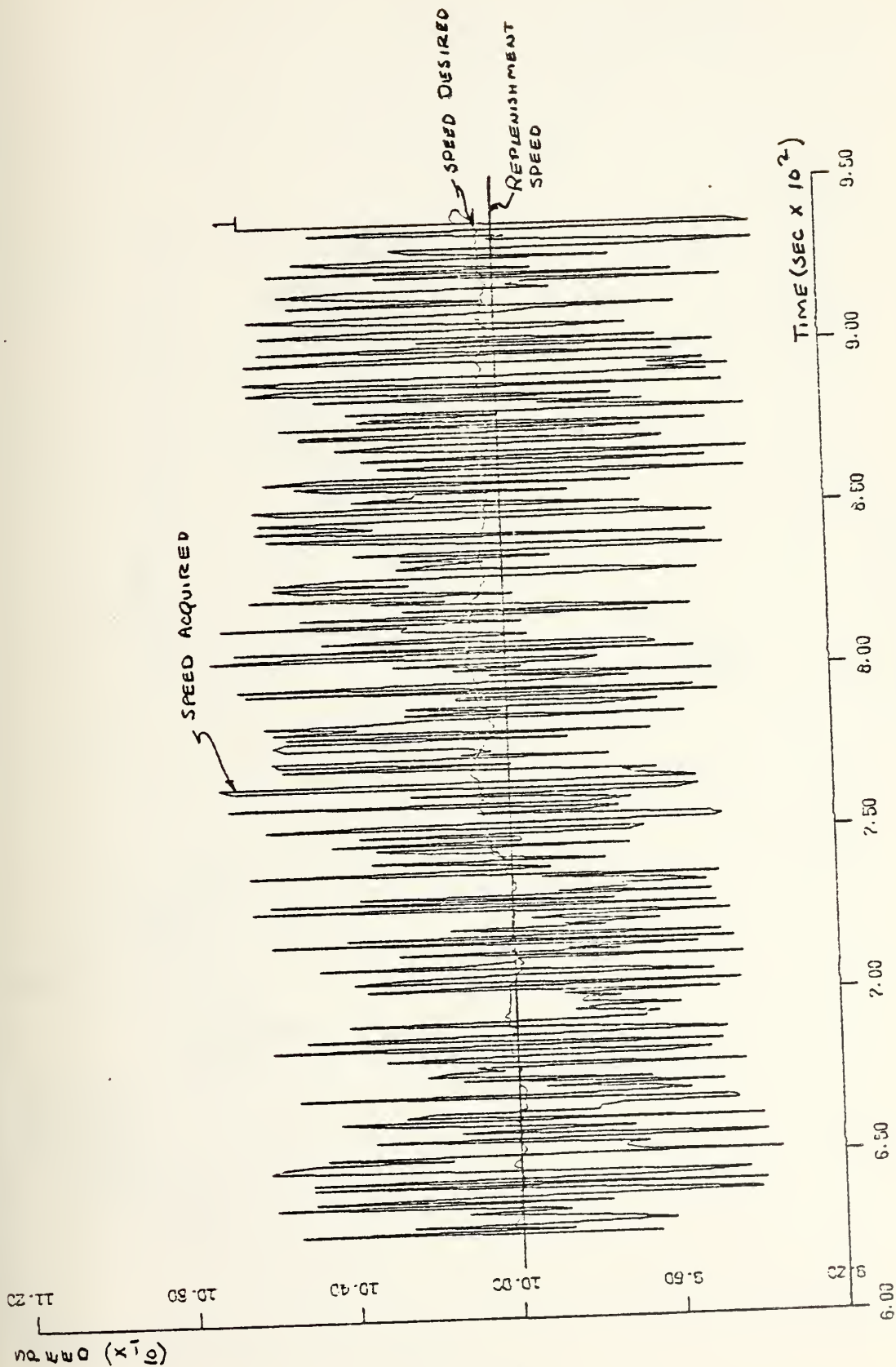


Figure III-104  
Turn Phase Speed Response in Waves

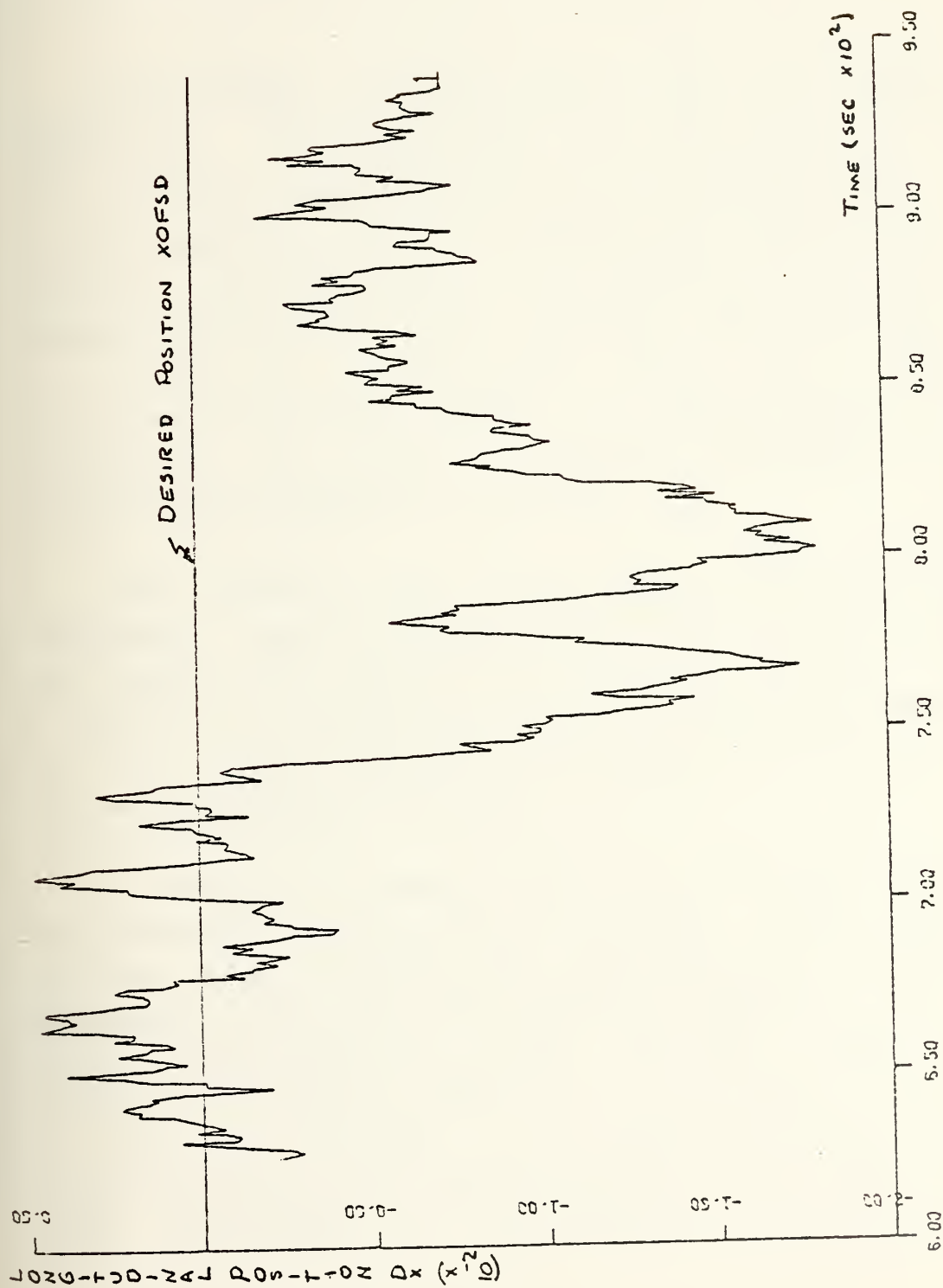


Figure III-105  
Turn Phase Longitudinal Position DX in Waves

#### IV. CONCLUSIONS AND RECOMMENDATIONS

##### A. CONCLUSIONS

The results of this design study have been most gratifying. The basic concepts initially perceived for the RAS control have been realized. The decoupled ship control in the RAS environment is a viable and plausible idea. This thesis contains a workable system for implementation of computer controlled RAS. The achievement of 2.3 foot maximum excursion for lateral distance while both ships are in a turn, and longitudinally offset by 53 feet is a phenomenal achievement. Having this kind of accuracy in RAS operations, can vastly increase the safety of this complicated and dangerous maneuver.

The approach phase of RAS can be a very hair raising experience. Night replenishment and sea state complicate the "seaman's eye" method now employed in the fleet. Having a system that automatically handles the approach regardless of the adverse conditions can, again, do nothing more than increase the safety of the RAS maneuver.

Schemes for computer control of nonlinear systems and the purposeful introduction of nonlinear control laws are becoming more practical with the technological advances in micro processors. The ever increasing number of U.S. Navy ships with computer systems installed, makes digital computer ship control realizable in the present time frame. A good micro computer or an existing installed computer (such as one used for the NTDS system) can be used in this vein. Procurement of the hardware required for this RAS

system can be dissipated over time periods contingent on the funding available. The supply ship requires only two reflectors for the range and bearing devices stationed on the receiving ship. All ships can be outfitted with such reflectors at a minimal cost, while the bulk of the hardware can be introduced to the ships at regularly scheduled yard periods.

In the initial conception of this thesis, a section was planned for open ocean maneuvering. After some research on this facet of ship control, it was determined that work in this area has already been documented<sup>[24]</sup><sup>[25]</sup>. The existence of NTDS outputs for station attainment and single ship control systems, made design in this area redundant.

The concept of integrated centralized ship control has been in the background for over a decade<sup>[26]</sup>. Although given a low priority due to funding considerations, its implementation seems to be just around the corner<sup>[27]</sup>. However, a review of ref. 27 indicates a lack of RAS capability. Whether this is an oversight in the article or neglected in the design criteria is unknown. If it has been neglected in the design, a very real problem has been overlooked. The recent incidences of ship collisions while conducting RAS<sup>[28]</sup> emphasizes the need for inclusion of this very dangerous maneuver in the "Integrated Bridge System." Lack of technology can no longer be used as an excuse. This thesis and other research reports<sup>[29]</sup> have advanced the implementation feasibility to a level that cannot be ignored. With these projects finalized in practical terms, their incorporation into fleet use is the next imperative step.

A major effort in this area must be made. The ever increasing complexities of today's naval ships and the loads being placed on the officers and men are such that computer

control must be used; and used now! We cannot afford the luxury of time to prove these systems<sup>①</sup> worth, but must make concerted efforts to get them implemented before the lives of 300+ men are lost.

Whenever a complicated system such as a ship in the RAS situation is encountered, many facets have to be concurrently analyzed. This fact has caused inclusion of many diagrams in this thesis to illustrate the total picture. Each run, with a different condition, requires many plots to analyze the differences in the responses and the causes of the differences. The computer programs shown do not reflect the actual run times in the JCL shown. As many as twenty plots were output in these programs in the times listed. Analysis of the actual computation times show that the algorithms run considerably under the time required for real time operation. The sampled data rate used in the simulations was 0.11 seconds. This is well within the realizable data rates available in even the slowest of today's computers and microprocessors. The thrust of this consideration is that there are no problems envisioned in converting RAS simulation to real world RAS control.

## E. RECOMMENDATIONS

In the heading control design section of this thesis, the need for a completely adaptive gain scheme was cited. Again in the velocity control section, when a longitudinal offset was introduced, this need became even more evident. The first and most important recommendation for further study is the development of just such an adaptive gain scheme.

The linear equations of motion should be replaced with nonlinear equations to validate the control designs advanced

in this thesis. Along with this, the hydrodynamic coefficients for the Navy's modern ships are required to be able to design these control systems for today's vessels.

It is further recommended that a concerted effort be made to obtain data on the interactive forces and moments between ships of dissimilar types and sizes. These forces and moments must also be available for sea state conditions. In fact, the whole area on sea state effects on the various ship types in the RAS situation and in open ocean maneuvering needs attention. Not enough data was available for this researcher to be able to pinpoint sea state effects on ship hulls. Since replenishment at sea is rarely conducted in the sterile condition of calm sea, these considerations are of utmost importance to allow testing of any control system in the simulation stage of development.

The intent here is not to imply that the control systems portrayed in this thesis are the best for the RAS scenario, but that the procedures used can be applied to any control scheme desired and benchmarked to the ones contained here. As previously mentioned, much meaningful research and design must be accomplished to allow system reliability and, more important, system acceptability by the officers and men who will ultimately trust their lives to it. This is a task that must not be taken lightly.

## APPENDIX A

Due to the lengthy nature of the computer programs presented in this thesis, many functions and subroutines were developed to simplify their presentation. This appendix lists these functions and subroutines in alphabetical order. The computer programs reference this appendix and indicate the placement of the required functions and subroutines.

A brief description for each listing is given to aid the reader in determining their purpose and use. The following is a listing of the functions and subroutines contained in this appendix in the order presented:

SUBROUTINE BOXPLX  
FUNCTION DEGRAD  
FUNCTION DELAY  
FUNCTION FE - RUN A (FEA)  
FUNCTION FE - RUN E (FEB)  
FUNCTION FE - RUN C (FEC)  
SUBROUTINE HDGRAS  
FUNCTION KE  
MAIN PROGRAM FOR FUNCTION MINIMIZATIONS (MINIEXPX)  
SUBROUTINE RBMEAS  
FUNCTION RKLDEQ  
SUBROUTINE SLOPES  
FUNCTION SPINIT  
FUNCTION SPDCTR  
FUNCTION SEDOFC  
FUNCTION SPDREC  
FUNCTION SWCL  
SUBROUTINE SWITCH

SUBROUTINE SWTCHF  
SUBROUTINE TRANS  
FUNCTION XLIMIT

## SUBROUTINE EOXPX

This subroutine was used for all optimization runs in heading control and speed control. It was programmed locally and is part of the IBM 360 SSP library at the Naval Postgraduate School. A full explanation and description is shown in the first few pages of the subroutine listing.

SUBROUTINE BOXPLX

.....  
SUBROUTINE BOXPLX (CATEGORY H0)  
PURPOSE  
BOXPLX IS A SUBROUTINE USED TO SOLVE THE PROBLEM OF LOCATING  
A MINIMUM (OR MAXIMUM) OF AN ARBITRARY OBJECTIVE FUNCTION  
SUBJECT TO ARBITRARY EXPLICIT AND/OR IMPLICIT CONSTRAINTS BY  
THE COMPLEX METHOD OF M.J. BOX. EXPLICIT CONSTRAINTS ARE  
DEFINED AS UPPER AND LOWER BOUNDS ON THE INDEPENDENT VARIABLES.  
IMPLICIT CONSTRAINTS MAY BE ARBITRARY FUNCTIONS OF THE VAR-  
IABLES. TWO FUNCTION SUBPROGRAMS TO EVALUATE THE OBJECTIVE  
FUNCTION AND IMPLICIT CONSTRAINTS, RESPECTIVELY, MUST BE  
SUPPLIED BY THE USER (SEE EXAMPLE PROGRAMMING). BOXPLX ALSO HAS  
THE OPTION TO PERFORM INTEGER PROGRAMMING, WHERE THE VALUES  
OF THE INDEPENDENT VARIABLES ARE RESTRICTED TO INTEGERS.  
USAGE  
CALL BOXPLX (NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)  
DESCRIPTION OF PARAMETERS  
NV AN INTEGER INPUT DEFINING THE NUMBER OF INDEPENDENT  
VARIABLES OF THE OBJECTIVE FUNCTION TO BE MINIMIZED.  
NOTE: MAXIMUM NV + NAV IS PRESENTLY 50. MAXIMUM NV IS  
25. IF THESE LIMITS MUST BE EXCEEDED, PUNCH A SOURCE  
DECK IN THE USUAL MANNER, AND CHANGE THE DIMENSION  
STATEMENTS.  
NAV AN INTEGER INPUT DEFINING THE NUMBER OF AUXILIARY VAR-  
IABLES THE USER WISHES TO DEFINE FOR HIS OWN CONVENIENCE.  
TYPICALLY HE MAY WISH TO DEFINE THE VALUE OF EACH IMPLICIT  
CONSTRAINT FUNCTION AS AN AUXILIARY VARIABLE. IF THIS  
IS DONE, THE OPTIONAL OUTPUT FEATURE OF BOXPLX CAN BE  
USED TO OBSERVE THE VALUES OF THOSE CONSTRAINTS AS THE  
SOLUTION PROGRESSES. AUXILIARY VARIABLES, IF USED,  
SHOULD BE EVALUATED IN FUNCTION KE (DEFINED BELOW).  
NAV MAY BE ZERO.  
NPR INPUT INTEGER CONTROLLING THE FREQUENCY OF OUTPUT DESIRED

CC

FOR DIAGNOSTIC PURPOSES. IF NPR .LE. 0, NO OUTPUT WILL BE  
PRODUCED BY BOXPLX. OTHERWISE, THE CURRENT COMPLEX OF  
K= 2\*NV VERTICES AND THEIR CENTROID WILL BE OUTPUT AFTER  
EACH NPR PERMISSIBLE TRIALS. THE NUMBER OF TOTAL TRIALS,  
NUMBER OF FEASIBLE TRIALS, NUMBER OF FUNCTION EVALUATIONS,  
AND NUMBER OF IMPLICIT CONSTRAINT EVALUATIONS ARE IN-  
CLUDED IN THE OUTPUT.  
ADDITIONALLY, (WHEN NPR .GT. 0) THE SAME INFORMATION  
WILL BE OUTPUT:

- 1) IF THE INITIAL POINT IS NOT FEASIBLE, GENERATED,
- 2) AFTER THE FIRST COMPLETE COMPLEX IS GENERATED,
- 3) IF A FEASIBLE VERTEX CANNOT BE FOUND AT SOME TRIAL,
- 4) IF THE OBJECTIVE VALUE OF A VERTEX CANNOT BE MADE  
NO-LONGER-WORST.
- 5) IF THE LIMIT ON TRIALS (NTA) IS REACHED AND,
- 6) WHEN THE OBJECTIVE FUNCTION HAS BEEN UNCHANGED FOR  
2\*NV TRIALS, INDICATING A LOCAL MINIMUM HAS BEEN  
FOUND.

IF THE USER WISHES TO TRACE THE PROGRESS OF A SOLUTION,  
A CHOICE OF NPR = 25, 50 OR 100 IS RECOMMENDED.

NTA INTEGER INPUT OF LIMIT ON THE NUMBER OF TRIALS ALLOWED  
IN THE CALCULATION. IF THE USER INPUTS NTA .LE. 0, A  
DEFAULT VALUE OF 2000 IS USED. WHEN THIS LIMIT IS REACHED  
CONTROL RETURNS TO THE CALLING PROGRAM WITH THE BEST  
ATTAINED OBJECTIVE FUNCTION VALUE IN YMN, AND THE BEST  
ATTAINED SOLUTION POINT IN XS.

R A REAL NUMBER INPUT TO DEFINE THE FIRST RANDOM NUMBER  
USED IN DEVELOPING THE INITIAL COMPLEX OF 2\*NV VERTICES.  
(0. .GT. R .LT. 1.) IF R IS NOT WITHIN THESE BOUNDS,  
IT WILL BE REPLACED BY 1./3. .

XS INPUT REAL ARRAY DIMENSIONED AT LEAST NV+NAV. THE FIRST  
NV MUST CONTAIN A FEASIBLE ORIGIN FOR STARTING THE CAL-  
CULATION. THE LAST NAV NEED NOT BE INITIALIZED. UPON  
RETURN FROM BOXPLX, THE FIRST NV ELEMENTS OF THE ARRAY  
CONTAIN THE COORDINATES OF THE MINIMUM OBJECTIVE FUNCTION,  
AND THE REMAINING NAV (NAV-GE. 0) CONTAIN THE VALUES OF  
THE CORRESPONDING AUXILIARY VARIABLES.

IP INTEGER INPUT FOR OPTIONAL INTEGER PROGRAMMING. IF IP=1,  
THE VALUES OF THE INDEPENDENT VARIABLES WILL BE REPLACED  
WITH INTEGER VALUES (STILL STORED AS REAL\*4).

XU A REAL ARRAY DIMENSIONED AT LEAST NV INPUTTING THE UPPER

CC









```
BXPX2840
BXPX2850
BXPX2860
BXPX2870
BXPX2880
BXPX2890
BXPX2900
BXPX2910
BXPX2920
BXPX2930
BXPX2940
BXPX2950
BXPX2960
BXPX2970
BXPX2980
BXPX2990
BXPX3000
BXPX3010
BXPX3020
BXPX3030
BXPX3040
BXPX3050
BXPX3060
BXPX3070
BXPX3080
BXPX3090
BXPX3100
BXPX3110
BXPX3120
BXPX3130
BXPX3140
BXPX3150
BXPX3160
BXPX3170
BXPX3180
BXPX3190
BXPX3200
BXPX3210
BXPX3220
BXPX3230
BXPX3240
BXPX3250
BXPX3260
BXPX3270
BXPX3280
BXPX3290
BXPX3300
BXPX3310
```

COMPARISON WITH OTHER METHODS", COMPUTER JOURNAL, 8 APR. '65,  
PP. 45-52.

BEVERIDGE G., AND SCHECHTER R., "OPTIMIZATION: THEORY AND  
PRACTICE", MCGRAW-HILL, 1970.

PROGRAMMER

R.R. HILLEARY 1/1966.  
REVISED FOR SYSTEM 360 4/1967  
CORRECTED 1/1969  
REVISED/EXTENDED BY L.NOLAN/R.HILLEARY 2/1975

.....

SUBROUTINE BOXPLX (NV,NAV,NPR,NTZ,RZ,XS,IP,BU,BL,YMN,IER)

DIMENSION V(50,50), FUN(50), SUM(25), CEN(25), XS(NV), BU(NV), BL(  
INV)

KV = 5  
EP = 1.E-6  
NTA = 2000  
IF (NTZ.GT.0) NTA = NTZ  
R = RZ  
IF (R.LE.0..OR.R.GE.1.) R=1./3.  
NVT = NV+NAV

TOTAL VARS, EXPLICIT PLUS IMPLICIT

NT = 0  
CURRENT TRIAL NO.

NPT = 0  
CURRENT NO. OF PERMISSIBLE TRIALS

NTFS = 0  
CURRENT NO. OF TIMES F HAS BEEN ALMOST UNCHANGED

CHECK FEASIBILITY OF START POINT

DO 4 I=1,NV  
VT = XS(I)  
IF (BL(I).LE.VT) GO TO 1  
II = -I  
VT = BL(I)  
GO TO 2  
1 IF (BU(I).GE.VT) GO TO 3  
II = I

```

BX PX 33320
BX PX 33330
BX PX 33340
BX PX 33350
BX PX 33360
BX PX 33370
BX PX 33380
BX PX 33390
BX PX 33400
BX PX 33410
BX PX 33420
BX PX 33430
BX PX 33440
BX PX 33450
BX PX 33460
BX PX 33470
BX PX 33480
BX PX 33490
BX PX 33500
BX PX 33510
BX PX 33520
BX PX 33530
BX PX 33540
BX PX 33550
BX PX 33560
BX PX 33570
BX PX 33580
BX PX 33590
BX PX 33600
BX PX 33610
BX PX 33620
BX PX 33630
BX PX 33640
BX PX 33650
BX PX 33660
BX PX 33670
BX PX 33680
BX PX 33690
BX PX 33700
BX PX 33710
BX PX 33720
BX PX 33730
BX PX 33740
BX PX 33750
BX PX 33760
BX PX 33770
BX PX 33780
BX PX 33790

```

BXPX3800  
 BXPX3810  
 BXPX3820  
 BXPX3830  
 BXPX3840  
 BXPX3850  
 BXPX3860  
 BXPX3870  
 BXPX3880  
 BXPX3890  
 BXPX3900  
 BXPX3910  
 BXPX3920  
 BXPX3930  
 BXPX3940  
 BXPX3950  
 BXPX3960  
 BXPX3970  
 BXPX3980  
 BXPX3990  
 BXPX4000  
 BXPX4010  
 BXPX4020  
 BXPX4030  
 BXPX4040  
 BXPX4050  
 BXPX4060  
 BXPX4070  
 BXPX4080  
 BXPX4090  
 BXPX4100  
 BXPX4110  
 BXPX4120  
 BXPX4130  
 BXPX4140  
 BXPX4150  
 BXPX4160  
 BXPX4170  
 BXPX4180  
 BXPX4190  
 BXPX4200  
 BXPX4210  
 BXPX4220  
 BXPX4230  
 BXPX4240  
 BXPX4250  
 BXPX4260  
 BXPX4270

```

C      IF (LIMIT,GE,NLIM) GO TO 11
C      DO 8 J=1,NV
C      RANDOM NUMBER GENERATOR (RANDU)
      IQR = IQR*65539
      IF (IQR.LT.0) IQR = IQR+2147483647+1
      RQX = IQR
      RQX = RQX*.4656613E-9
      V(J,I) = BL(J)+RQX*(BU(J)-BL(J))
      IF (IP.EQ.1) V(J,I)=AINT(V(J,I)+.5)
8     CONTINUE
C
      DO 10 L=1,NLIM
      NCE = NCE+1
      IF (KE(V(1,I)).EQ.0) GO TO 13
C
      DO 9 J=1,NV
      VT = .5*(V(J,I)+CEN(J))
      IF (IP.EQ.1) VT = AINT(VT+.5)
      V(J,I) = VT
9     CONTINUE
C
10    CONTINUE
C
11    IF (NPR.LE.0) GO TO 12
      WRITE (6,51) I
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,I,FUN,CEN,I)
12    IER = -1
      GO TO 48
C
13    DO 14 J=1,NV
      SUM(J) = SUM(J)+V(J,I)
14    CEN(J) = SUM(J)/FI
C
      TRY TO ASSURE FEASIBLE CENTROID FOR STARTING.
      NCE = NCE+1
      IF (KE(CEN).NE.0) GO TO 7
      NFE = NFE+1
      FUN(I) = FE(V(1,I))
15    CONTINUE
C
      END OF LOOP SETTING OF INITIAL COMPLEX.
      IF (NPR.LE.0) GO TO 17
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
C
      FIND THE WORST VERTEX, THE 'J'TH.
      J = 1
  
```

```

C      DO 16 I=2,K
C      IF (FUN(J).GE.FUN(I)) GO TO 16
C      J=I
C      16 CONTINUE
C      BASIC LOOP.  ELIMINATE EACH WORST VERTEX IN TURN.  IT MUST BECOME
C      NO LONGER WORST, NOT MERELY IMPROVED.  FIND NEXT-TO-WORST VERTEX,
C      THE 'JN,TH ONE.
C      17 JN = 1
C      IF (J.EQ.1) JN = 2
C      DO 18 I=1,K
C      IF (I.EQ.J) GO TO 18
C      IF (FUN(JN).GE.FUN(I)) GO TO 18
C      JN = I
C      18 CONTINUE
C      LIMIT = NUMBER OF MOVES DURING THIS TRIAL TOWARD THE CENTROID
C      DUE TO FUNCTION VALUE.
C      LIMIT = 1
C      COMPUTE CENTROID AND OVER REFLECT WORST VERTEX.
C      DO 19 I=1,NV
C      VT = V(I,J)
C      SUM(I) = SUM(I)-VT
C      CEN(I) = SUM(I)/FKM
C      VT = BETA*CEN(I)-ALPHA*VT
C      IF (IP.EQ.1) VT = AINT(VT+.5)
C      INSURE THE EXPLICIT CONSTRAINTS ARE OBSERVED.
C      19 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C      NT = NT+1
C      CHECK FOR IMPLICIT CONSTRAINT VIOLATION.
C      20 DO 25 N=1,NLIM
C      NCE = NCE+1
C      IF (KE(V(1,J)).EQ.0) GO TO 26
C      EVERY 'KV,TH TIME, OVER-REFLECT THE OFFENDING VERTEX THROUGH THE
C      BEST VERTEX.
C      IF (MOD(N,KV).NE.0) GO TO 22
C      CALL FBV (K,FUN,M)
C      DO 21 I=1,NV

```

```

BXPX4280
BXPX4290
BXPX4300
BXPX4310
BXPX4320
BXPX4330
BXPX4340
BXPX4350
BXPX4360
BXPX4370
BXPX4380
BXPX4390
BXPX4400
BXPX4410
BXPX4420
BXPX4430
BXPX4440
BXPX4450
BXPX4460
BXPX4470
BXPX4480
BXPX4490
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BXPX4540
BXPX4550
BXPX4560
BXPX4570
BXPX4580
BXPX4590
BXPX4600
BXPX4610
BXPX4620
BXPX4630
BXPX4640
BXPX4650
BXPX4660
BXPX4670
BXPX4680
BXPX4690
BXPX4700
BXPX4710
BXPX4720
BXPX4730
BXPX4740
BXPX4750

```

```

VT = BETA*V(I,M)-ALPHA*V(I,J)
IF (IP.EQ.1) VT = AINT(VT+.5)
21 V(I,J) = AMAX1(AMINI(VT,BU(I)),BL(I))
C
GO TO 24
C
CONSTRAINT VIOLATION: MOVE NEW POINT TOWARD CENTROID.
C
22 DO 23 I=1,NV
VT = .5*(CEN(I)+V(I,J))
IF (IP.EQ.1) VT = AINT(VT+.5)
V(I,J) = VT
23 CONTINUE
C
24 NT = NT+1
25 CONTINUE
C
IER = 1
C
CANNOT GET FEASIBLE VERTEX BY MOVING TOWARD CENTROID,
OR BY OVER-REFLECTING THRU THE BEST VERTEX.
IF (NPR.LE.0) GO TO 42
WRITE (6,52) NT,J
CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FJN,CEN,J)
GO TO 42
C
FEASIBLE VERTEX FOUND, EVALUATE THE OBJECTIVE FUNCTION.
26 NFE=NFE+1
FUNTRY = FE(V(1,J))
C
TEST TO SEE IF FUNCTION VALUE HAS NOT CHANGED.
AFO = ABS(FUNTRY-FUNOLD)
AMX = AMAX1(ABS(EP*FUNOLD),EP)
C
ACTIVATE THE FOLLOWING TWO STATEMENTS FOR DIAGNOSTIC PURPOSES ONLY.
WRITE (6,99) J,AFO,AMX,FUNTRY,FUNOLD,FUN(J),FUN(JN),NTFS,N
99 FORMAT (1X,I3,6E15.7,2I5)
IF (AFO.GT.AMX) GO TO 27
NTFS = NTFS+1
IF (NTFS.LT.NCT) GO TO 28
IER = 0
IF (NPR.LE.0) GO TO 42
WRITE (6,53) K
GO TO 42
27 NTFS = 0
C
IS THE NEW VERTEX NO LONGER WORST?
28 IF (FUNTRY.LT.FUN(JN)) GO TO 34

```

```

C TRIAL VERTEX IS STILL WORST; ADJUST TOWARD CENTROID.
C EVERY KV,TH TIME, OVER-REFLECT THE OFFENDING VERTEX THROUGH THE
C BEST VERTEX.
C   LIMIT = LIMIT+1
C   IF (MOD(LIMIT,KV).NE.0) GO TO 30
C   CALL FBV (K,FUN,M)
C
C   DO 29 I=1,NV
C   VT = BETA*V(I,M) - ALPHA*V(I,J)
C   IF (IP.EQ.1) VT = AINT(VT+.5)
C   29 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
C   GO TO 32
C
C   DO 30 I=1,NV
C   VT = .5*(CEN(I)+V(I,J))
C   IF (IP.EQ.1) VT = AINT(VT+.5)
C   30 V(I,J) = VT
C   31 CONTINUE
C
C   32 IF (LIMIT.LT.NLIM) GO TO 33
C
C   CANNOT MAKE THE 'J',TH VERTEX NO LONGER WORST BY DISPLACING TOWARD
C   THE CENTROID OR BY OVER-REFLECTING THRU THE BEST VERTEX.
C   IER = 2
C   IF (NPR.GT.0) WRITE (6,52) NT,J
C   GO TO 42
C   33 NT = NT+1
C   GO TO 20
C
C   SUCCESS: WE HAVE A REPLACEMENT FOR VERTEX J.
C   34 FUN(J) = FUNTRY
C   FUNOLD = FUNTRY
C   NPT = NPT+1
C
C   EVERY 100,TH PERMISSIBLE TRIAL, RECOMPUTE CENTROID SUMMATION TO
C   AVOID CREEPING ERROR.
C   IF (MOD(NPT,100).NE.0) GO TO 37
C
C   DO 36 I=1,NV
C   SUM(I) = 0.
C
C   DO 35 N=1,K
C   SUM(I) = SUM(I)+V(I,N)
C
C   CEN(I) = SUM(I)/FK
C   36 CONTINUE

```

BXPX5240  
 BXPX5250  
 BXPX5260  
 BXPX5270  
 BXPX5280  
 BXPX5290  
 BXPX5300  
 BXPX5310  
 BXPX5320  
 BXPX5330  
 BXPX5340  
 BXPX5350  
 BXPX5360  
 BXPX5370  
 BXPX5380  
 BXPX5390  
 BXPX5400  
 BXPX5410  
 BXPX5420  
 BXPX5430  
 BXPX5440  
 BXPX5450  
 BXPX5460  
 BXPX5470  
 BXPX5480  
 BXPX5490  
 BXPX5500  
 BXPX5510  
 BXPX5520  
 BXPX5530  
 BXPX5540  
 BXPX5550  
 BXPX5560  
 BXPX5570  
 BXPX5580  
 BXPX5590  
 BXPX5600  
 BXPX5610  
 BXPX5620  
 BXPX5630  
 BXPX5640  
 BXPX5650  
 BXPX5660  
 BXPX5670  
 BXPX5680  
 BXPX5690  
 BXPX5700  
 BXPX5710

BXPX5720  
 BXPX5730  
 BXPX5740  
 BXPX5750  
 BXPX5760  
 BXPX5770  
 BXPX5780  
 BXPX5790  
 BXPX5800  
 BXPX5810  
 BXPX5820  
 BXPX5830  
 BXPX5840  
 BXPX5850  
 BXPX5860  
 BXPX5870  
 BXPX5880  
 BXPX5890  
 BXPX5900  
 BXPX5910  
 BXPX5920  
 BXPX5930  
 BXPX5940  
 BXPX5950  
 BXPX5960  
 BXPX5970  
 BXPX5980  
 BXPX5990  
 BXPX6000  
 BXPX6010  
 BXPX6020  
 BXPX6030  
 BXPX6040  
 BXPX6050  
 BXPX6060  
 BXPX6070  
 BXPX6080  
 BXPX6090  
 BXPX6100  
 BXPX6110  
 BXPX6120  
 BXPX6130  
 BXPX6140  
 BXPX6150  
 BXPX6160  
 BXPX6170  
 BXPX6180  
 BXPX6190

```

C      LC = 0
C      GO TO 39
C
C      37 DO 38 I=1,NV
C      38 SUM(I) = SUM(I)+V(I,J)
C
C      LC = J
C
C      39 IF (NPR.LE.0) GO TO 40
C      IF (MOD(NPT,NPR).NE.0) GO TO 40
C
C      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,LC)
C
C      HAS THE MAX. NUMBER OF TRIALS BEEN REACHED WITHOUT CONVERGENCE?
C      IF NOT, GO TO NEW TRIAL.
C      40 IF (NT.GE.NTA) GO TO 41
C
C      NEXT-TO-WORST VERTEX NOW BECOMES WORST.
C      J = JN
C      GO TO 17
C      41 IER = 3
C      IF (NPR.GT.0) WRITE (6,54)
C
C      COLLECTOR POINT FOR ALL ENDINGS.
C      1) CANNOT DEVELOP FEASIBLE VERTEX.
C      2) CANNOT DEVELOP A NO-LONGER-WORST VERTEX.
C      3) FUNCTION VALUE UNCHANGED FOR K TRIALS.
C      4) LIMIT ON TRIALS REACHED.
C      5) CANNOT FIND FEASIBLE VERTEX AT START.
C
C      IER = 1
C      IER = 2
C      IER = 0
C      IER = 3
C      IER = -1
C
C      42 CONTINUE
C
C      FIND BEST VERTEX.
C      CALL FBV (K,FUN,M)
C      IF (IER.GE.3) GO TO 44
C
C      RESTART IF THIS SOLUTION IS SIGNIFICANTLY BETTER THAN THE PREVIOUS,
C      OR IF THIS IS THE FIRST TRY.
C      IF (NPR.LE.0) GO TO 43
C      WRITE (6,55) (M,YMN,FUN(M))
C      43 IF (FUN(M).GE.YMN) GO TO 47
C      IF (ABS(FUN(M)-YMN).LE.AMAX1(EP,EP*YMN)) GO TO 47
C
C      GIVE IT ANOTHER TRY UNLESS LIMIT ON TRIALS REACHED.
C      44 YMN = FUN(M)
C      FUN(1) = FUN(M)
C
C      DO 45 I=1,NV
  
```

```

C      CEN(I) = V(I,M)
      SUM(I) = V(I,M)
45     V(I,1) = V(I,M)
C
      DO 46 I=1,NVT
46     XS(I) = V(I,M)
C
      IF (IER.LT.3) GO TO 6
47     IF (NPR.LE.0) GO TO 48
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,V(1,M),-1)
48     WRITE (6,56) FUN(M)
      RETURN
C
49     FORMAT (50H) INDEX AND DIRECTION OF OUTLYING VARIABLE AT START(I5)
50     FORMAT (50H) IMPLICIT CONSTRAINT VIOLATED AT START. DEAD END. )
51     FORMAT (50H) CANNOT FIND FEASIBLE, I4, TH VERTEX OR CENTROID AT START
      I=1
52     FORMAT (10H) AT TRIAL I4,54H CANNOT FIND FEASIBLE VERTEX WHICH IS
      IO LONGER WORST, I4,15X, RESTART FROM BEST VERTEX. )
53     FORMAT (40H) FUNCTION HAS BEEN ALMOST UNCHANGED FOR I5,7H TRIALS)
54     FORMAT (27H) LIMIT ON TRIALS EXCEEDED. )
55     FORMAT (50H) BEST VERTEX IS NO., I3, OLD MIN WAS , E15.7,
      I=1, NEW MIN IS , E15.7)
56     FORMAT (50H) MIN OBJECTIVE FUNCTION IS , E15.7)
      END
      SUBROUTINE FBV (K,FUN,M)
      DIMENSION FUN(50)
      M = 1
C
      DO 1 I=2,K
      IF (FUN(M).LE.FUN(I)) GO TO 1
      M = I
1     CONTINUE
C
      RETURN
      END
      SUBROUTINE BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FN,C,IK)
      DIMENSION V(50,50), FN(50), C(25)
      WRITE (6,4) NT,NPT,NFE,NCE
C
      DO 1 I=1,K
      WRITE (6,5) FN(I), (V(J,I), J=1,NV)
      IF (NVT.LE.NV) GO TO 1
      NVP = NV+1
      WRITE (6,6) (V(J,I), J=NVP,NVT)
1     CONTINUE
C
      IF (IK.NE.0) GO TO 2

```

```

BX PX 6200
BX PX 6210
BX PX 6220
BX PX 6230
BX PX 6240
BX PX 6250
BX PX 6260
BX PX 6270
BX PX 6280
BX PX 6290
BX PX 6300
BX PX 6310
BX PX 6320
BX PX 6330
BX PX 6340
BX PX 6350
BX PX 6360
BX PX 6370
BX PX 6380
BX PX 6390
BX PX 6400
BX PX 6410
BX PX 6420
BX PX 6430
BX PX 6440
BX PX 6450
BX PX 6460
BX PX 6470
BX PX 6480
BX PX 6490
BX PX 6500
BX PX 6510
BX PX 6520
BX PX 6530
BX PX 6540
BX PX 6550
BX PX 6560
BX PX 6570
BX PX 6580
BX PX 6590
BX PX 6600
BX PX 6610
BX PX 6620
BX PX 6630
BX PX 6640
BX PX 6650
BX PX 6660
BX PX 6670

```

BXPX6680  
 BXPX6690  
 BXPX6700  
 BXPX6710  
 BXPX6720  
 BXPX6730  
 BXPX6740  
 BXPX6750  
 BXPX6760  
 BXPX6770  
 BXPX6780  
 BXPX6790  
 BXPX6800  
 BXPX6810  
 BXPX6820  
 BXPX6830  
 BXPX6840  
 BXPX6850  
 BXPX6860

```

WRITE (6,7) (C(I), I=1,NV)
RETURN
2 IF (IK,GE,0) GO TO 3
WRITE (6,8) (C(I), I=1,NV)
RETURN
3 WRITE (6,9) IK, (C(I), I=1,NV)
RETURN

```

```

4  FORMAT (,'NO. TOTAL TRIALS = ',I5,4X,'NO. FEASIBLE TRIALS = ',I5,4X,'NO. CONSTRAINT EVALUATIONS = ',I5,4X,'NO. INDEPENDENT VARIABLES/DEPENDENT VARIABLES = ',I5,4X)
5  FORMAT (,'NO. FUNCTION EVALUATIONS = ',I5,4X,'NO. CONSTRAINT EVALUATIONS = ',I5,4X,'NO. INDEPENDENT VARIABLES/DEPENDENT VARIABLES = ',I5,4X)
6  FORMAT (,'NO. FUNCTION EVALUATIONS = ',I5,4X,'NO. CONSTRAINT EVALUATIONS = ',I5,4X,'NO. INDEPENDENT VARIABLES/DEPENDENT VARIABLES = ',I5,4X)
7  FORMAT (,'NO. FUNCTION EVALUATIONS = ',I5,4X,'NO. CONSTRAINT EVALUATIONS = ',I5,4X,'NO. INDEPENDENT VARIABLES/DEPENDENT VARIABLES = ',I5,4X)
8  FORMAT (,'NO. FUNCTION EVALUATIONS = ',I5,4X,'NO. CONSTRAINT EVALUATIONS = ',I5,4X,'NO. INDEPENDENT VARIABLES/DEPENDENT VARIABLES = ',I5,4X)
9  FORMAT (,'NO. FUNCTION EVALUATIONS = ',I5,4X,'NO. CONSTRAINT EVALUATIONS = ',I5,4X,'NO. INDEPENDENT VARIABLES/DEPENDENT VARIABLES = ',I5,4X)
END

```

۷

5

## FUNCTION DEGRAD

This function was programmed to convert degrees to radians and radians to degrees. A third purpose is to convert degrees to a range of 0-360. It is used extensively throughout the programs, functions, and subroutines listed in this thesis.

# FUNCTION DEGRAD

```

C C C C C C C C C C C C C C C C
FUNCTION DEGRAD (NDRFLG,NSHFLG,FUNCT)
FUNCTION TO CONVERT DEGREES TO RADIAN AND RADIANS TO
DEGREES AND SHIFT THE DEGREES TO A RANGE BETWEEN 000.0
AND 360.0 IN ACCORDANCE WITH THE FOLLOWING FLAG
DEFINITIONS
NDRFLG 0 - CONVERT RADIAN TO DEGREES
        1 - CONVERT DEGREES TO RADIAN
        2 - DO NOT CONVERT
NSHFLG 0 - CONVERT ANGLES(DEG) TO THE RANGE BETWEEN 000.0
        1 - DO NOT CONVERT
        AND 360.0
        1 - DO NOT CONVERT
FUNCU = FUNCT
IF (NDRFLG.EQ.2) GO TO 2
IF (NDRFLG.EQ.1) GO TO 1
FUNCU = FUNCU*180.0/3.141592654
GO TO 2
1 FUNCU = FUNCU*3.141592654/180.0
GO TO 5
2 IF (NSHFLG.EQ.1) GO TO 5
3 IF (FUNCU.LT.360.0) GO TO 4
FUNCU = FUNCU-360.0
GO TO 3
4 IF (FUNCU.GE.0.0) GO TO 5
FUNCU = FUNCU+360.0
GO TO 4
5 DEGRAD = FUNCU
RETURN
END
DGRD 10
DGRD 20
DGRD 30
DGRD 40
DGRD 50
DGRD 60
DGRD 70
DGRD 80
DGRD 90
DGRD 100
DGRD 110
DGRD 120
DGRD 130
DGRD 140
DGRD 150
DGRD 160
DGRD 170
DGRD 180
DGRD 190
DGRD 200
DGRD 210
DGRD 220
DGRD 230
DGRD 240
DGRD 250
DGRD 260
DGRD 270
DGRD 280
DGRD 290
DGRD 300
DGRD 310
DGRD 320

```

## FUNCTION DELAY

This function is used as the time delay in the speed control optimization runs. It was designed to be used as an equivalence to DELY in DSL simulation. The following variables are defined:

E(I) is the storage array (should be initialized before the first function call)  
K is the delay step count  
SPDDES is the variable to be delayed for K steps  
P is the flag for delay or no delay  
     $P \geq 0.0$  delay SPDDES  
     $P < 0.0$  function output equal to SPDDES

The function stores the input value (SPDDES) in E(M) and decrements the value in array E(I) at each call of the function until the value is in the position of E(1). The value is then output from the function delayed K intervals.

# FUNCTION DELAY

```

C
FUNCTION DELAY (K,P,SPDDES,E)
DIMENSION E(10)
M = K+1
E(M) = SPDDES
DO 1 I=1,K
1 E(I) = E(I+1)
IF (P.LT.0.0) GO TO 2
DELAY = E(1)
RETURN
2 DELAY = SPDDES
RETURN
END
C

```

```

DELY 10
DELY 20
DELY 30
DELY 40
DELY 50
DELY 60
DELY 70
DELY 80
DELY 90
DELY 100
DELY 110
DELY 120
DELY 130
DELY 140

```

## FUNCTION FE - RUN A

### FEA

This function is the simulation for heading control optimization of the approach phase. It is called by subroutine EOXP LX. The integration step size is 0.04 with a final time of 20.0. In this function all initial conditions are set to zero except initial geographic location and speed. The reference ship maintains a straight course and the control ship starts its approach 5 ship lengths astern and 0.4 ship lengths laterally displaced to starboard of the reference ship.

The function is referred to as function FEA in the text.

```

C      FUNCTION FE (Z)
C      EVALUATION OF COST FUNCTION AS A FUNCTION OF RSENS,WTSENS,RGN
C      DIMENSION Z(8),Y(20),YDOT(20),X(20),XDOT(20)
C      REAL *8XDOT,XDOT,TD
C      HYDRODYNAMIC COEFFICIENTS
      A11 = 0.015
      B11 = 0.01243
      A21 = 0.00027
      B21 = 0.0051
      A12 = 0.000197
      B12 = 0.00351
      A22 = 0.00068
      B22 = 0.00227
      A33 = 0.0085
      B33 = 0.0012
      XKA = 0.0027
      XKB = -0.00126
      XNC = 0.0012
      D = A11*A22-A21*A12
      XKC = 0.0
      XLUC = 20.84765
      DLIDM = 2.0
      DLTEM = 7.0
      XKG = DLIDM/DLTEM
      D2D = 0.0
C      IDENTIFICATION OF GAINS TO BE FOUND
      RSENS = Z(1)
      WTSENS = Z(2)
      RGN = Z(3)
      VFBG = 0.0
C      INITIAL CONDITIONS
      DO 1 J=1,14
1    Y(J) = 0.0
C      INITIAL GEOGRAPHIC LOCATION
      Y(5) = 5.0
      Y(6) = 0.0
      Y(10) = 0.0
      Y(11) = 0.4
C      OTHER INITIALIZATIONS
      N = 1
      RD = 1.0
FEZA 10
FEZA 20
FEZA 30
FEZA 40
FEZA 50
FEZA 60
FEZA 70
FEZA 80
FEZA 90
FEZA 100
FEZA 110
FEZA 120
FEZA 130
FEZA 140
FEZA 150
FEZA 160
FEZA 170
FEZA 180
FEZA 190
FEZA 200
FEZA 210
FEZA 220
FEZA 230
FEZA 240
FEZA 250
FEZA 260
FEZA 270
FEZA 280
FEZA 290
FEZA 300
FEZA 310
FEZA 320
FEZA 330
FEZA 340
FEZA 350
FEZA 360
FEZA 370
FEZA 380
FEZA 390
FEZA 400
FEZA 410
FEZA 420
FEZA 430

```

FEZA 440  
FEZA 450  
FEZA 460  
FEZA 470  
FEZA 480  
FEZA 490  
FEZA 500  
FEZA 510  
FEZA 520  
FEZA 530  
FEZA 540  
FEZA 550  
FEZA 560  
FEZA 570  
FEZA 580  
FEZA 590  
FEZA 600  
FEZA 610  
FEZA 620  
FEZA 630  
FEZA 640  
FEZA 650  
FEZA 660  
FEZA 670  
FEZA 680  
FEZA 690  
FEZA 700  
FEZA 710  
FEZA 720  
FEZA 730  
FEZA 740  
FEZA 750  
FEZA 760  
FEZA 770  
FEZA 780  
FEZA 790  
FEZA 800  
FEZA 810  
FEZA 820  
FEZA 830  
FEZA 840  
FEZA 850  
FEZA 860  
FEZA 870  
FEZA 880  
FEZA 890  
FEZA 900  
FEZA 910

```

IS = 1
DD = 0.2
DI = 0.0
D2 = 0.0
YY1 = 0.0
YY2 = 0.0
YN1 = 0.0
YN2 = 0.0
SPEED = 0.0
INITIALIZATIONS
Y(4) = 1.0
U02 = 1.5
CDO12 = 1.5
DISTANCE = 1.5
DYO = Y(10)-Y(5)
DX0 = Y(11)-Y(6)
CALL TRANS (Y(2), DX0, DYO, ADX, ADY)
CALL SLOPES (ADX, ADY, YY1, YY2, YN1, YN2)
INITIALIZE TIME
T = 0.0
DT = 0.04
JT = 0
SHIP A
XIF11 = XKA*D1
XIF21 = XKB*D1
XIF31 = XKC*D1 + XNC
XI11 = -B11*Y(1) - B21*Y(3) + XIF11
XI21 = -B12*Y(1) - B22*Y(3) + XIF21
XI31 = -B31*Y(4) + XIF31
YDO1(1) = (XI11*A22 - XI21*A21)/D
YDO1(2) = Y(3)
YDO1(3) = (XI21*A11 - XI11*A12)/D
YDO1(4) = XI31/A33
YDO1(5) = Y(4)*COS(Y(2)) - Y(1)*SIN(Y(2))
YDO1(6) = Y(4)*SIN(Y(2)) + Y(1)*COS(Y(2))
SHIP B
XIF12 = XKA*D2 + YY2
XIF22 = XKB*D2 + YN2
XIF32 = XKC*D2 + XNC
XI12 = -B11*Y(7) - B21*Y(9) + XIF12
XI22 = -B12*Y(7) - B22*Y(9) + XIF22
CDO12 = -SPDCR(ADX, U02)
XI32 = -B33*CDO12 + XIF32
YDO1(7) = (XI12*A22 - XI22*A21)/D
YDO1(8) = Y(9)
YDO1(9) = (XI22*A11 - XI12*A12)/D
YDO1(10) = CDO12*COS(Y(8)) - Y(7)*SIN(Y(8))
YDO1(11) = CDO12*SIN(Y(8)) + Y(7)*COS(Y(8))
DX = Y(10) - Y(5)

```

```

DY = Y(11)-Y(6)
CALL TRANS (Y(2),DX,DY,ADX,ADY)
CALL SLOPES (ADX,ADY,Y(1),Y(2),Y(1),Y(2))
YAWD2 = DEGRAD(0,0,Y(8))
CALL RBMEAS (N,Y(2),Y(5),Y(6),Y(8),Y(10),Y(11),RD,R1,B1,BB1,R2,B2,
1BB2)
CALL HDGRAS (N,IS,R1,B1,BB1,R2,B2,BB2,RSENS,Y(8),PSIDFD,PSIADD,PSI
1DED,WT,DA,AID,BID,B2D,WTSENS,DD,RD)
BCOT2D = DEGRAD(0,1,Y(9))
BDOTFB = VFBC*BDOT2D
DDUMB = YAWD2-PSIDED+BDOTFB
IF (DDUMB.GT.180.0) DDUMB=DDUMB-360.0
IF (DDUMB.LT.-180.0) DDUMB=360.0+DDUMB
DLTS = XLIMIT(-30.0,30.0,DDUMB*RGH)
DLTE = DLTS-D2D
DLTBE = XLIMIT(-DLTEM,DLTEM,DLTE)
YDOT(14) = XKG*DLTBE*XLUC
D2D = Y(14)
D2 = DEGRAD(1,1,D2D)
DTRAN = T*ABS(D2)
YDOT(12) = DTRAN
DISTE = T*10.0*ABS(DD-ADY)
YDOT(13) = DISTE
OBJ = Y(12)+Y(13)

DO 3 J=1,14
X(J) = DBLE(Y(J))
3 XDOT(J) = DBLE(YDOT(J))

TD = DBLE(T)
DTD = DBLE(DT)
ZS = RKLDEQ(14,X,XDOT,TD,DTD,JT)

DO 4 J=1,14
Y(J) = SNGL(X(J))
4 YDOT(J) = SNGL(XDOT(J))

T = SNGL(TD)
DT = SNGL(DTD)
IF (ZS-1.) 5,2,6
5 WRITE (6,8)
6 STOP
6 IF (T.GT.20.0) GO TO 7
7 GO TO 2
7 FE = OBJ
WRITE (6,9) OBJ,RSENS,WTSENS,RGH
RETURN

```

FEZAI400  
FEZAI410  
FEZAI420  
FEZAI430

```
8 FORMAT (' RKLDEQ RETURNED VALUE LT 1.0, INTEGRATION PROBLEM')  
9 FORMAT (' EXIT FUNCTION FE(Z) OBJ= ', F15.8, ' RSENS= ', F15.8, '  
1 WTSENS= ', F15.8, ' RGN= ', F15.8)  
END
```

FUNCTION FE - RUN B  
FEB

This function is the simulation for heading control optimization of the turn phase. It is called by subroutine BOXPLX. The integration step size is 0.04 with a final time of 20.0. In this function, the following initial conditions are non-zero:

control ship rudder angle D2D & Y(14) = 8.7 degrees  
lateral displacement Y(11) = 0.2  
reference ship's speed U01 & Y(4) = 1.0  
control ship's speed U02 & CDCT2 = 1.5 (after first  
step becomes 1.0)

The reference ship's rudder is activated to 5.0 degrees between time 4.0 and 5.0. The runs were for port side replenishment.

The function is referred to as function FEB in the text.

C	FUNCTION FE (Z)	FEZB	10
	EVALUATION OF COST FUNCTION AS A FUNCTION OF RSENS,WTSENS,RGN	FEZB	20
	DIMENSION Z(8),Y(20),YDOT(20),X(20),XDOT(20)	FEZB	30
C	REAL *8XDOT,X,DOT,TD	FEZB	40
	HYDRODYNAMIC COEFFICIENTS	FEZB	50
	A11 = 0.015	FEZB	60
	B11 = 0.01243	FEZB	70
	A21 = 0.00027	FEZB	80
	B21 = 0.0051	FEZB	90
	A12 = 0.000197	FEZB	100
	B12 = 0.00351	FEZB	110
	A22 = 0.00068	FEZB	120
	B22 = 0.00227	FEZB	130
	A33 = 0.0085	FEZB	140
	B33 = 0.0012	FEZB	150
	XKA = 0.0027	FEZB	160
	XKB = -0.00125	FEZB	170
	XNC = 0.0012	FEZB	180
	D = A11*A22-A21*A12	FEZB	190
	XKC = 0.0	FEZB	200
	XLUC = 20.84765	FEZB	210
	DLTDM = 2.0	FEZB	220
	DLTEM = 7.0	FEZB	230
	XKG = DLTDM/DLTEM	FEZB	240
	D10 = 0.0	FEZB	250
	D2D = 8.7	FEZB	260
C	IDENTIFICATION OF GAINS TO BE FOUND	FEZB	270
	RSENS = Z(1)	FEZB	280
	WTSENS = Z(2)	FEZB	290
	RGN = Z(3)	FEZB	300
C	VFBG = Z(4)	FEZB	310
C	INITIAL CONDITIONS	FEZB	320
	DO 1 J=1,14	FEZB	330
	1 Y(J) = 0.0	FEZB	340
C	INITIAL GEOGRAPHIC LOCATION	FEZB	350
C	Y(5) = 0.0	FEZB	360
	Y(6) = 0.0	FEZB	370
	Y(10) = 0.0	FEZB	380
	Y(11) = 0.2	FEZB	390
	Y(14) = 8.7	FEZB	400
C	OTHER INITIALIZATIONS	FEZB	410
		FEZB	420
		FEZB	430

```

N = 1
RD = 1.0
IS = 1.0
DD = 0.2
D1 = 0.0
D2 = DEGRAD(1,1,D2D)
YY1 = 0.0
YY2 = 0.0
YN1 = 0.0
YN2 = 0.0
SPEED INITIALIZATIONS
Y(4) = 1.0
U01 = 1.0
U02 = 1.5
CDOI2 = 1.5
DISTANCE INITIALIZATION
DY0 = Y(10)-Y(5)
DX0 = Y(11)-Y(6)
CALL TRANS (Y(2),DX0,DY0,ADX,ADY)
CALL SLOPES (ADX,ADY,YY1,YY2,YN1,YN2)
INITIALIZE TIME
T = 0.0
DT = 0.04
JT = 0
SHIP A
2 DIDES = 0.0
IF ((T-GE.4.0).AND.(T.LE.5.0)) DIDES=5.0
DLTSL = XLIMIT(-30.0,30.0,DIDES)
DLTSL-DID
DLTBE1 = XLIMIT(-DLTEM,DLTEM,DLTSL)
YDOT(12) = XKG*DLTBE1*XLUC
Y(12)
DID = DEGRAD(1,1,DID)
D1 = DEGRAD(1,1,D1D)
XIF11 = XKA*D1
XIF21 = XKB*D1
XIF31 = XKC*D1 +XNC
XI11 = -B11*Y(1)-B22*Y(3)+XIF11
XI21 = -B12*Y(1)-B22*Y(3)+XIF21
XI31 = -B33*Y(4)+XIF31
YDOT(1) = (XI11*A22-XI21*A21)/D
YDOT(2) = Y(3)
YDOT(3) = (XI21*A11-XI11*A12)/D
YDOT(4) = XI31/A33
YDOT(5) = Y(4)*COS(Y(2))-Y(1)*SIN(Y(2))
YDOT(6) = Y(4)*SIN(Y(2))+Y(1)*COS(Y(2))
YAWD1 = DEGRAD(0,0,Y(2))
SHIP B
XIF12 = XKA*D2+YY2

```

```

FEZB 440
FEZB 450
FEZB 460
FEZB 470
FEZB 480
FEZB 490
FEZB 500
FEZB 510
FEZB 520
FEZB 530
FEZB 540
FEZB 550
FEZB 560
FEZB 570
FEZB 580
FEZB 590
FEZB 600
FEZB 610
FEZB 620
FEZB 630
FEZB 640
FEZB 650
FEZB 660
FEZB 670
FEZB 680
FEZB 690
FEZB 700
FEZB 710
FEZB 720
FEZB 730
FEZB 740
FEZB 750
FEZB 760
FEZB 770
FEZB 780
FEZB 790
FEZB 800
FEZB 810
FEZB 820
FEZB 830
FEZB 840
FEZB 850
FEZB 860
FEZB 870
FEZB 880
FEZB 890
FEZB 900
FEZB 910

```

```

XIF22 = XKB*D2+YN2
XIF32 = XKC*D2+XNC
XI12 = -B11*Y(7)-B21*Y(9)+XIF12
XI22 = -B12*Y(7)-B22*Y(9)+XIF22
XD0T2 = SPDCR(ADX,U01,U02)
XD0T2 = -B33*XD0T2+XIF32
YD0T(7) = (XI12*A22-XI22*A21)/D
YD0T(8) = Y(9)
YD0T(9) = (XI22*A11-XI12*A12)/D
YD0T(10) = CD0T2*COS(Y(8))-Y(7)*SIN(Y(8))
YD0T(11) = CD0T2*SIN(Y(8))+Y(7)*COS(Y(8))
DX = Y(10)-Y(5)
DY = Y(11)-Y(6)
CALL TRANS (Y(2),DX,DY,ADX,ADY)
CALL SLOPES (ADX,ADY,Y(1),Y(2),Y(1),Y(2))
YAWD2 = DEGRAD(0.0,Y(8))
CALL RBMEAS (N,Y(2),Y(5),Y(6),Y(8),Y(10),Y(11),RD,R1,B1,BB1,R2,B2,
1 BB2)
CALL HDGRAS (N,IS,R1,B1,BB1,R2,B2,BB2,RSENS,Y(8),PSIDFD,PSIADD,PSI
1 DED,WT,DA,A1D,B1D,B2D,WISENS,DD,RD)
BD0T2D = DEGRAD(0.1,Y(9))
BD0TFB = VFBG*BD0T2D
DDUMB = YAWD2-PSIDED+BD0TFB
IF (DDUMB.GT.180.0) DDUMB=DDUMB-360.0
IF (DDUMB.LT.-180.0) DDUMB=360.0+DDUMB
DLIS = XLIMIT(-30.0,30.0,DDUMB*RGN)
DLIE = DLIS-D2D
DLIBE = XLIMIT(-DLIEM,DLIEM,DLIE)
YD0T(14) = XKG*DLTBE*XLUC
D2D = Y(14)
D2 = DEGRAD(1,1,D2D)
DISTIE = ABS(DD-ADY)
YD0T(13) = DISTIE
OBJ = Y(13)

C
D0 3 J=1,14
X(J) = DBLE(Y(J))
3 XD0T(J) = DBLE(YD0T(J))
C
TD = DBLE(T)
DTD = DBLE(DT)
ZS = RKLDEQ(14,X,XD0T,TD,DTD,JT)
C
D0 4 J=1,14
Y(J) = SNGL(X(J))
4 YD0T(J) = SNGL(X(J))
C
T = SNGL(TD)

```

```

FEZB 920
FEZB 930
FEZB 940
FEZB 950
FEZB 960
FEZB 970
FEZB 980
FEZB 990
FEZB 1000
FEZB 1010
FEZB 1020
FEZB 1030
FEZB 1040
FEZB 1050
FEZB 1060
FEZB 1070
FEZB 1080
FEZB 1090
FEZB 1100
FEZB 1110
FEZB 1120
FEZB 1130
FEZB 1140
FEZB 1150
FEZB 1160
FEZB 1170
FEZB 1180
FEZB 1190
FEZB 1200
FEZB 1210
FEZB 1220
FEZB 1230
FEZB 1240
FEZB 1250
FEZB 1260
FEZB 1270
FEZB 1280
FEZB 1290
FEZB 1300
FEZB 1310
FEZB 1320
FEZB 1330
FEZB 1340
FEZB 1350
FEZB 1360
FEZB 1370
FEZB 1380
FEZB 1390

```

```

      DT = SNGL(DTD)
      IF (ZS-1.) 5,2,6
5 WRITE (6,8)
      STOP
6 IF (T.GT.20.0) GO TO 7
      GO TO 2
7 FE = OBJ
      WRITE (6,9) OBJ,ADY,ADX,YAWD1,YAWD2,D2D
      RETURN
      C
8 FORMAT (' RKLDEQ RETURNED VALUE LT 1.0; INTEGRATION PROBLEM' )
9 FORMAT (' EXIT FUNCTION FE(2),OBJ=',F15.8,';ADY=',F15.8,';ADX=',
1 F15.8,';5X,YAWD1=',F15.8,';YAWD2=',F15.8,';D2D=',F15.8)
      END
FEZB1400
FEZB1410
FEZB1420
FEZB1430
FEZB1440
FEZB1450
FEZB1460
FEZB1470
FEZB1480
FEZB1490
FEZB1500
FEZB1510
FEZB1520
FEZB1530

```

FUNCTION FE - RUN C  
FEC

This function is the simplified simulation for speed control optimization of the switching function SW. It is called by subroutine BOXPLX. The function shown is for approach speed of 1.1 and a replenishment speed of 1.0. The runs were made for various realistic combinations to obtain an optimum switching curve.

The run used a step size of 0.04 and a final time of 10.0. The two ships were run linearly with only the longitudinal direction and motion of any concern.

This function is referred to as function FEC in the text.

FUNCTION FE - RUN C

```

C      FUNCTION FE (Z)  X(10), XDOT(10), Y(10), YDOT(10), E(10)
C      DIMENSION Z(8), XDOT(10), YDOT(10), E(10)
C      REAL *8XDOT,X,DID,TD
C      IDENTIFICATION OF GAINS
C      SW=Z(1)
C      INITIAL CONDITIONS
C      N=2
C      APOX = 1.1
C      BPOX = 0.0
C
C      DO 1 I=1,N
C      Y(I) = 0.0
C      1 YDOT(I) = 0.0
C
C      DO 2 I=1,10
C      E(I) = 0.0
C
C      SPDO1 = 1.0
C      SPDO2 = 1.1
C      Y(1) = 1.1
C      XK1 = 1.012425
C      P = -1.0
C      A = 22.0
C      G = 0.092
C      XLUC = 20.84765
C      UF = 21.73
C      XK = UF/A
C      T = 0.0
C      DT = 0.04
C      JT = 0
C      SPDDER = XK1*SPDO1
C      ADX = BPOX-APOX
C      ITERATION LOOP
C      3 IF (T.GT.0.24) P = 4.88/XLUC
C      IF (ABS(ADX).GT.2.0) GO TO 9
C      SPDDER = XK1*(SPDREC(ADX,SPDO1,SPDO2,SW)-SPDO1)
C      SPDDER = DELAY(6,P,SPDDER,E)
C      SPDIN = XK*(SPDDEL+SPDDER)
C      SPDDER = G*(SPDIN-Y(1))
C      YDOT(1) = SPDDER*XLUC
C      YDOT(2) = T*ABS(ADX)
C      OBJ = Y(2)

```

```

C      DO 4 I=1,N
        X(I) = DBLE(Y(I))
        4 XDOT(I) = DBLE(YDOT(I))
C
        TD = DBLE(T)
        DTD = DBLE(DT)
        ZS = RKLDEQ(N,X,XDOT,TD,DTD,JT)
C
        DO 5 I=1,N
            Y(I) = SNGL(X(I))
            5 YDOT(I) = SNGL(XDOT(I))
C
            T = SNGL(TD)
            DT = SNGL(DTD)
            IF (ZS-1.) 6,3,7
            6 WRITE (6,10)
            7 STOP
            IF (T.GT.10.0) GO TO 8
            APOSX = APOSX+SPDOI*DT
            BPOSX = BPOSX+Y(1)*DT
            ADX = BPOSX-APOSX
            GO TO 3
            8 FE = OBJ
              WRITE (6,11) OBJ,SW,ADX,Y(1)
              RETURN
            9 FE = 1.0E06
              WRITE (6,12) ADX
              RETURN
C
            10 FORMAT (' RKLDEQ RETURNED ZS FLAG LT 0.0, INTEGRATION PROBLEM')
            11 FORMAT (' EXIT FUNCTION FE(Z) OBJ=',F15.8,5X,'SW=',F15.8,/,
            12 22X,'ADX=',F15.8,5X,'FINAL SPEED=',F15.8)
            12 FORMAT (' EXIT FUNCTION FE(Z) ABS(ADX).GT.2.0, ADX=',F15.8)
            END
FEZC 440
FEZC 450
FEZC 460
FEZC 470
FEZC 480
FEZC 490
FEZC 500
FEZC 510
FEZC 520
FEZC 530
FEZC 540
FEZC 550
FEZC 560
FEZC 570
FEZC 580
FEZC 590
FEZC 600
FEZC 610
FEZC 620
FEZC 630
FEZC 640
FEZC 650
FEZC 660
FEZC 670
FEZC 680
FEZC 690
FEZC 700
FEZC 710
FEZC 720
FEZC 730
FEZC 740
FEZC 750
FEZC 760
FEZC 770
FEZC 780

```

## SUBROUTINE HDGRAS

This subrcutine was programmed to calculate the desired heading (FSIDES) for RAS heading control. It uses the outputs of subroutine RBMEAS to calculate this heading with gains RSENS and WTSENS. The large number of outputs in the subroutine call statement were made for ease of DSL printed output for tracking of simulation accuracy.

The subroutine also incorporates a loop to avoid computer precision problems in the ARSIN function.

# SUBROUTINE HDGRAS

```

SUBROUTINE HDGRAS (N,IS,R1,B1,BB1,R2,B2,BB2,RSENS,PSIB,PSIDFD,PSIA,HDGR
1DD,PSIDED,DA,AID,BID,B2D,WTSENS,DD,D) HDGR 20
SUBROUTINE TO CALCULATE DESIRED HEADING FOR RAS HDGR 30
IF N SET TO 1 HDGRAS WILL BE USED HDGR 40
IF (N.NE.1) GO TO 4 HDGR 50
IS DENOTES THE SIDE OF APPROACH OF RECEIVING SHIP IS=1 PORT, HDGR 60
IS=0 STBD HDGR 70
RSENS - ADDITIONAL HEADING SENSITIVITY DUE TO SEPARATION DISTANCE HDGR 80
RSENS=1.0 CORRESPONDS TO 10.87 DEG/10FT FO A 527 FT HDGR 90
SHIP HDGR 100
PSIDFD - ADDITIONAL HEADING DUE TO HEADING DIFFERENCE(WEIGHTED) HDGR 110
PSIADD - ADDITIONAL HEADING DUE TO DISTANCE ERROR(WEIGHTED) HDGR 120
PSIDED - TOTAL DESIRED HEADING=PSIDFD(WEIGHTED)+PSIADD(WEIGHTED) HDGR 130
NOTE ALL RETURNED VALUES ENDING IN "D" ARE IN DEGREES HDGR 140
WTSENS - WEIGHTING FACTOR GAIN FOR DIFFERENCE IN HEADINGS HDGR 150
DA - CG ABS DISTANCE BETWEEN SHIPS HDGR 160
AID - CG REL BEARING BETWEEN SHIPS HDGR 170
HEADING DIFFERENCE HDGR 180
ARG = (R1*SIN(B1))-R2*SIN(B2))/D HDGR 190
IF (ARG.GT.1.0) GO TO 1 HDGR 200
IF (ARG.LT.-1.0) GO TO 2 HDGR 210
PSIDIF = ARSIN(ARG) HDGR 220
GO TO 3 HDGR 230
1 PSIDIF = ARSIN(1.0) HDGR 240
GO TO 3 HDGR 250
2 PSIDIF = ARSIN(-1.0) HDGR 260
3 CONTINUE HDGR 270
CG DISTANCE HDGR 280
DA = (R1+R2)/2.0 HDGR 290
CG RELATIVE BEARING HDGR 300
AA1 = (BB1+BB2)/2.0 HDGR 310
INITIAL SENSE OF APPROACH SIDE DESIRED DISTANCE HDGR 320
DDC = DD HDGR 330
IF (IS.EQ.0) DDC = -DD HDGR 340
ADDITIONAL HEADING DUE TO DISTANCE HDGR 350
PSIADC = RSENS*(DDC+DA*SIN(AA1)) HDGR 360
TOTAL DESIRED HEADING HDGR 370
PSIDES = PSIADC+WTSENS*PSIDIF+PSIB HDGR 380
CONVERT RADIAN TO DEGREES HDGR 390
HDGR 400
HDGR 410
HDGR 420
HDGR 430

```

```

HDGR 440
HDGR 450
HDGR 460
HDGR 470
HDGR 480
HDGR 490
HDGR 500
HDGR 510
HDGR 520

```

```

PSIDFD = DEGRAD(0,0,0,PSIDIF)
PSIADD = DEGRAD(0,0,0,PSIADC)
PSIDED = DEGRAD(0,0,0,PSIDES)
A1 = 6.283185307+AA1
A1D = DEGRAD(0,0,A1)
B1D = DEGRAD(0,0,B1)
B2D = DEGRAD(0,0,B2)
4 RETURN
END

```

## FUNCTION KE

This function is required by all optimization runs. It is the function that contains constraints for subrcutine BOXPLX. No constraints are present, consequently function KE is set equal to 0.

FUNCTION KE

FUNCTION KE (X)  
DIMENSION X(8)  
KE = 0  
RETURN  
END

KEX  
KEX  
KEX  
KEX  
KEX  
10  
20  
30  
40  
50

MAIN PROGRAM FOR FUNCTION MINIMIZATIONS  
MINIBXPX

This is a generalized program which calls subrcutine  
BOXFLX. Its main purpose is input and output of the values  
required in the optimization runs. This is referred to as  
MINIBXPX in the text.



## SUBROUTINE RBMEAS

This subrcutine measures the range and bearing of the forward and after stations which is required of subrcutine BDGRAS. This is done with trigncmetric functions as shown in chapter II. The subroutine is specifically designed to circumvent any ambiguities usually associated with these functions.

It is the basis of the decoupling of the two RAS ships that this thesis is based.

# SUBROUTINE RBMEAS

```

SUBROUTINE RBMEAS (N, PSIA, X1, Y1, PSIB, X2, Y2, D, R1, B1, BB1, R2, B2, BB2)
SUBROUTINE TO CALCULATE THE RELATIVE POSITIONS OF SHIP A (SUPPLY)
TO SHIP B (RECEIVING)
PSIA - HEADING OF SHIP A (RAD)
PSIB - HEADING OF SHIP B (RAD)
X1, Y1 - COORDINATES OF SHIP A
X2, Y2 - COORDINATES OF SHIP B
D - DISTANCE BETWEEN SENSORS (ALSO BETWEEN REFLECTORS) (SAME ON
      BOTH SHIPS)
R1, R2 - FWD, AFT MEASURED DISTANCE
B1, B2 - FWD, AFT RELATIVE BEARINGS (RAD)
BB1, BB2 - FWD, AFT RELATIVE BEARINGS (RAD) WITH SIGN
IF N SET TO 1, RBMEAS SUBROUTINE WILL BE USED
IF (N.EQ.1) GO TO 7
ANGLES AND DISTANCES FOR SENSOR INPUT
SDF1 = (D/2.0)*SIN(PSIA)
SDF2 = (D/2.0)*SIN(PSIB)
SDF3 = (D/2.0)*COS(PSIA)
SDF4 = (D/2.0)*COS(PSIB)
FWD DISTANCE
ADFX = SDF3+X1-SDF4-X2
ADFY = SDF1+Y1-SDF2-Y2
R1 = SQT(ADFX**2+ADFY**2)
AFT DISTANCE
ADAX = -SDF3+X1+SDF4-X2
ADAY = -SDF1+Y1+SDF2-Y2
R2 = SQT(ADAX**2+ADAY**2)
FWD ANGLE
IF (ADFY.EQ.0.0) GO TO 2
BB1 = ATAN2(ADFY, ADFX)
1 BB1 = BB1-PSIB
GO TO 3
2 BB1 = 1.570796327
IF (ADFY.LE.0.0) BB1=-BB1
GO TO 1
AFT ANGLE
IF (ADAX.EQ.0.0) GO TO 5
BB2 = ATAN2(ADAX, ADAY)
4 BB2 = BB2-PSIB
GO TO 6
5 BB2 = 1.570796327

```

RBMS 10  
 RBMS 20  
 RBMS 30  
 RBMS 40  
 RBMS 50  
 RBMS 60  
 RBMS 70  
 RBMS 80  
 RBMS 90  
 RBMS 100  
 RBMS 110  
 RBMS 120  
 RBMS 130  
 RBMS 140  
 RBMS 150  
 RBMS 160  
 RBMS 170  
 RBMS 180  
 RBMS 190  
 RBMS 200  
 RBMS 210  
 RBMS 220  
 RBMS 230  
 RBMS 240  
 RBMS 250  
 RBMS 260  
 RBMS 270  
 RBMS 280  
 RBMS 290  
 RBMS 300  
 RBMS 310  
 RBMS 320  
 RBMS 330  
 RBMS 340  
 RBMS 350  
 RBMS 360  
 RBMS 370  
 RBMS 380  
 RBMS 390  
 RBMS 400  
 RBMS 410  
 RBMS 420  
 RBMS 430

IF (ADAY.LE.0.0) BB2=-BB2  
GO TO 4  
6 CONTINUE  
7 RETURN  
END

RBMS 440  
RBMS 450  
RBMS 460  
RBMS 470  
RBMS 480

## FUNCTION RKLDEQ

This function is the Runge-Kutta-Gill forth-order integration used in all optimization runs. It is programmed locally and is part of the IBM 360 SSP library. A full explanation and description is shown in the first few pages of the function listing.

# FUNCTION RKLDEQ

FUNCTION RKLDEQ (FORTRAN 4,G/H) OR ASSEMBLER LANGUAGE)  
IDENTIFICATION D2-NPS-RKLDEQ, CHECKED OUT BY R. HILLEARY, 4/67.

PURPOSE  
THIS ROUTINE SOLVES A SYSTEM OF N FIRST-ORDER ORDINARY DIFFERENTIAL EQUATIONS BY THE RUNGE-KUTTA-GILL FOURTH-ORDER METHOD. ALL CALCULATIONS ARE IN DOUBLE-PRECISION.

USAGE --(WHEN USED BY FORTRAN CALLING PROGRAM)

S = RKLDEQ (N,Y,F,X,H,NT )

FOUR ENTRIES ARE REQUIRED TO ADVANCE THE SOLUTION FROM X TO X + H WHERE H IS THE INCREMENT. SEE SAMPLE PROBLEM FOR MORE INFORMATION

## DESCRIPTION OF PARAMETERS

- N - NUMBER OF FIRST-ORDER EQUATIONS IN SYSTEM TO BE SOLVED. (0.LE.N.LE.25).
- Y - NAME OF LINEAR ARRAY OF LENGTH AT LEAST N, IN WHICH SOLUTION VALUES WILL BE STORED BY RKLDEQ. THE CALLING PROGRAM SHOULD SUPPLY INITIAL VALUES BEFORE FIRST ENTRY.
- F - NAME OF LINEAR ARRAY OF LENGTH AT LEAST N, IN WHICH THE DERIVATIVES, COMPUTED IN USER'S CALLING PROGRAM, ARE STORED.
- X - THE INDEPENDENT VARIABLE, WHICH IS ADVANCED WITHIN RKLDEQ.
- H - THE INCREMENT FOR X, WHICH MAY BE CHANGED AT THE END OF ANY INTERVAL. (WHEN S=2.0)
- NT - AN INTEGER WHICH COUNTS THE NUMBER OF TIMES ENTRY TO RKLDEQ HAS BEEN MADE DURING THE CURRENT INTERVAL. IT MUST BE INITIALLY SET TO ZERO BY USER BEFORE FIRST CALL OF RKLDEQ. SUBSEQUENTLY IT SHOULD NOT BE CHANGED BY USER.
- S - A SWITCH TO BE TESTED BY USER UPON RETURN FROM RKLDEQ. IF S = 1.0, THE CALLING PROGRAM SHOULD NOW COMPUTE VALUES OF F, USING CURRENT VALUES OF X AND Y, AND THEN RETURN TO RKLDEQ. IF S=2.0, AND END OF PRESENT INTERVAL HAS BEEN REACHED. USER SHOULD STORE AND/OR OUTPUT CURRENT X AND/OR Y AND TEST FOR END OF COMPUTATION.

SEE SAMPLE PROBLEM.

RKLDFO003  
RKLDFO004  
RKLDFO005  
RKLDFO006  
RKLDFO007  
RKLDFO008  
RKLDFO009  
RKLDFO010  
RKLDFO011  
RKLDFO012  
RKLDFO013  
RKLDFO014  
RKLDFO015  
RKLDFO016  
RKLDFO017  
RKLDFO018  
RKLDFO019  
RKLDFO020  
RKLDFO021  
RKLDFO022  
RKLDFO023  
RKLDFO024  
RKLDFO025  
RKLDFO026  
RKLDFO027  
RKLDFO028  
RKLDFO029  
RKLDFO030  
RKLDFO031  
RKLDFO032  
RKLDFO033  
RKLDFO034  
RKLDFO035  
RKLDFO036  
RKLDFO037  
RKLDFO038  
RKLDFO039  
RKLDFO040  
RKLDFO041  
RKLDFO042  
RKLDFO043  
RKLDFO044

```

REMARKS
Y,F,X,AND H ARE DOUBLE PRECISION (REAL*8), RKLDEQ IS REAL*4.
MAXIMUM N IS NOW 25.
RKLDFF045
RKLDFF046
RKLDFF047
RKLDFF048
RKLDFF049
RKLDFF050
RKLDFF051
RKLDFF052
RKLDFF053
RKLDFF054
RKLDFF055
RKLDFF056
RKLDFF057
RKLDFF058
RKLDFF059
RKLDFF060
RKLDFF061
RKLD06A
RKLDFF062
RKLDFF063
RKLDFF064
RKLDFF065
RKLDFF066
RKLDFF067
RKLDFF068
RKLDFF069
RKLDFF070
RKLDFF071
RKLDFF072
RKLDFF073
RKLDFF074
RKLDFF075
RKLDFF076
RKLDFF077
RKLDFF078
RKLDFF079
RKLDFF080
RKLDFF081
RKLDFF082
RKLDFF083
RKLDFF084
RKLDFF085
RKLDFF086
RKLDFF087
RKLDFF088
RKLDFF089
RKLDFF090
RKLDFF091

NOTE
TWO DECKS EXIST FOR THIS FUNCTION. ONE IS IN F4 SOURCE LANGUAGE
THE OTHER IS ASSEMBLER LANGUAGE AND IS TO BE CALLED WITH A
FORTRAN TYPE CALLING SEQUENCE. RKLDEQ IS RETURNED IN F.P.REG.0

SAMPLE PROBLEM
DIMENSION Y(2), F(2)
REAL*8 Y,F,X,H
Y(1)=0.00
Y(2)=1.00
X=1.00
H=.0100
NT=0
WRITE (6,11) X,Y(1),Y(2)
CALCULATION OF DERIVATIVES0
1 F(1)=X*Y(1)-Y(2)*2
F(2)=Y(1)+DSQRT(X)
S=RKLDEQ(2,Y,F,X,H,NT)
IF (S-1.0) 10,1,2
ERROR STOP0
10 STOP
2 WRITE (6,11) X,Y(1),Y(2)
11 FORMAT (1X,3D25.13)
TEST FOR END OF COMPUTATION0
IF (DABS(X-2.500)-1.0D-5) 3,3,1
3 STOP
END
.....
FORTRAN 4 VERSION OF RUNGE-KUTTA-GILL ROUTINE
X,Y,F,H ARE DOUBLE-PRECISION. MAX N = 25
FUNCTION RKLDEQ (N,Y,F,X,H,NT)
REAL*8 Y,F,X,H,Q,H1,H2,H3,H6
DIMENSION Y(1),F(1),Q(25)
NT=NT+1
GO TO (1,2,3,4),NT
1 H1=H

```

RKLDF092  
 RKLDF093  
 RKLDF094  
 RKLDF095  
 RKLDF096  
 RKLDF097  
 RKLDF098  
 RKLDF099  
 RKLDF100  
 RKLDF101  
 RKLDF102  
 RKLDF103  
 RKLDF104  
 RKLDF105  
 RKLDF106  
 RKLDF107  
 RKLDF108  
 RKLDF109  
 RKLDF110  
 RKLDF111  
 RKLDF112  
 RKLDF113  
 RKLDF114  
 RKLDF115  
 RKLDF116  
 RKLDF117  
 RKLDF118  
 RKLDF119  
 RKLDF120

```

H2 = H1 * .5D0
H3 = H1 * 2.D0
H6 = H1/6.D0
DO 11 J = 1,N
11 Q(J) = 0.D0
A = .5D0
X = X + H2
GO TO 5

C
2 A = .2928932188134525
GO TO 5

C
3 A = 1.7071067811865475
X = X + H2
GO TO 5

C
4 DO 41 I = 1,N
41 Y(I) = Y(I) + H6 * F(I) - Q(I)/3.D0
NT = 0
RKLDEQ = 2.
GO TO 6

C
5 DO 51 L = 1,N
51 Y(L) = Y(L) + A * (H * F(L) - Q(L))
Q(L) = H3 * A * F(L) + (1.D0 - 3.D0 * A) * Q(L)
RKLDEQ = 1.

C
6 RETURN
END
  
```

## SUBROUTINE SLOPES

This subroutine contains the table look-up and interpolation scheme for the interactive forces and moments presented in the RAS environment. It is long and must be pre-compiled for most of the DSL simulation programs shown in this thesis.

## SUBROUTINE SLOPES

SUBROUTINE SLOPES (DX,DY,YY1,YY2,YN1,YN2)		TABLE LOOK-UP AND INTERPOLATION	
DIMENSION Z(23,16), W(23,16), X(23), Y(16)			
X(1)	= -1.1		
X(2)	= -1.9		
X(3)	= -.8		
X(4)	= -.7		
X(5)	= -.6		
X(6)	= -.5		
X(7)	= -.4		
X(8)	= -.3		
X(9)	= -.2		
X(10)	= -.1		
X(11)	= 0.		
X(12)	= .1		
X(13)	= .2		
X(14)	= .3		
X(15)	= .4		
X(16)	= .5		
X(17)	= .6		
X(18)	= .7		
X(19)	= .8		
X(20)	= .9		
X(21)	= 1.		
X(22)	= 1.		
X(23)	= 1.		
Y(1)	= 0.	10	
Y(2)	= 0.	12	
Y(3)	= 0.	14	
Y(4)	= 0.	16	
Y(5)	= 0.	18	
Y(6)	= 0.	22	
Y(7)	= 0.	24	
Y(8)	= 0.	26	
Y(9)	= 0.	28	
Y(10)	= 0.	30	
Y(11)	= 0.	32	
Y(12)	= 0.	34	
Y(13)	= 0.	36	
Y(14)	= 0.	38	
Y(15)	= 0.	40	
Y(16)	= 0.	42	
Z(1,1)	= 0.		

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[illegible]

Z(4,2) 33.  
Z(4,3) -28.  
Z(4,4) -23.  
Z(4,5) -18.  
Z(4,6) -16.  
Z(4,7) -14.  
Z(4,8) -12.  
Z(4,9) -10.  
Z(4,10) -8.  
Z(4,11) -6.  
Z(4,12) -4.  
Z(4,13) -2.  
Z(4,14) 0.  
Z(4,15) 0.  
Z(4,16) 0.  
Z(5,1) -38.  
Z(5,2) -31.  
Z(5,3) -26.  
Z(5,4) -21.  
Z(5,5) -18.  
Z(5,6) -14.  
Z(5,7) -12.  
Z(5,8) -10.  
Z(5,9) -8.  
Z(5,10) -6.  
Z(5,11) -4.  
Z(5,12) -2.  
Z(5,13) 0.  
Z(5,14) 0.  
Z(5,15) 0.  
Z(5,16) 0.  
Z(6,1) -28.  
Z(6,2) -24.  
Z(6,3) -20.  
Z(6,4) -15.  
Z(6,5) -12.  
Z(6,6) -10.  
Z(6,7) -8.  
Z(6,8) -6.  
Z(6,9) -4.  
Z(6,10) -2.  
Z(6,11) 0.  
Z(6,12) 0.  
Z(6,13) 0.  
Z(6,14) 0.  
Z(6,15) 0.  
Z(7,1) -15.

SLOP 920  
SLOP 930  
SLOP 940  
SLOP 950  
SLOP 960  
SLOP 970  
SLOP 980  
SLOP 990  
SLOP 1000  
SLOP 1010  
SLOP 1020  
SLOP 1030  
SLOP 1040  
SLOP 1050  
SLOP 1060  
SLOP 1070  
SLOP 1080  
SLOP 1090  
SLOP 1100  
SLOP 1110  
SLOP 1120  
SLOP 1130  
SLOP 1140  
SLOP 1150  
SLOP 1160  
SLOP 1170  
SLOP 1180  
SLOP 1190  
SLOP 1200  
SLOP 1210  
SLOP 1220  
SLOP 1230  
SLOP 1240  
SLOP 1250  
SLOP 1260  
SLOP 1270  
SLOP 1280  
SLOP 1290  
SLOP 1300  
SLOP 1310  
SLOP 1320  
SLOP 1330  
SLOP 1340  
SLOP 1350  
SLOP 1360  
SLOP 1370  
SLOP 1380  
SLOP 1390

Z(7,2)	=	-11.
Z(7,3)	=	-9.
Z(7,4)	=	-6.
Z(7,5)	=	-4.
Z(7,6)	=	-2.
Z(7,7)	=	0.
Z(7,8)	=	0.
Z(7,9)	=	0.
Z(7,10)	=	0.
Z(7,11)	=	0.
Z(7,12)	=	0.
Z(7,13)	=	0.
Z(7,14)	=	0.
Z(7,15)	=	0.
Z(7,16)	=	0.
Z(8,1)	=	4.
Z(8,2)	=	6.
Z(8,3)	=	7.
Z(8,4)	=	8.
Z(8,5)	=	9.
Z(8,6)	=	10.
Z(8,7)	=	7.
Z(8,8)	=	6.
Z(8,9)	=	4.
Z(8,10)	=	2.
Z(8,11)	=	0.
Z(8,12)	=	0.
Z(8,13)	=	0.
Z(8,14)	=	0.
Z(8,15)	=	0.
Z(8,16)	=	0.
Z(9,1)	=	27.
Z(9,2)	=	25.
Z(9,3)	=	22.
Z(9,4)	=	21.
Z(9,5)	=	18.
Z(9,6)	=	16.
Z(9,7)	=	14.
Z(9,8)	=	12.
Z(9,9)	=	10.
Z(9,10)	=	8.
Z(9,11)	=	6.
Z(9,12)	=	4.
Z(9,13)	=	2.
Z(9,14)	=	0.
Z(9,15)	=	52.
Z(9,16)	=	
Z(10,1)	=	



Z(13,2)78.  
Z(13,3)69.  
Z(13,4)60.  
Z(13,5)53.  
Z(13,6)48.  
Z(13,7)43.  
Z(13,8)38.  
Z(13,9)34.  
Z(13,10)31.  
Z(13,11)28.  
Z(13,12)25.  
Z(13,13)22.  
Z(13,14)19.  
Z(13,15)17.  
Z(13,16)15.  
Z(14,1)80.  
Z(14,2)70.  
Z(14,3)63.  
Z(14,4)55.  
Z(14,5)50.  
Z(14,6)45.  
Z(14,7)40.  
Z(14,8)36.  
Z(14,9)33.  
Z(14,10)30.  
Z(14,11)29.  
Z(14,12)26.  
Z(14,13)23.  
Z(14,14)20.  
Z(14,15)18.  
Z(14,16)16.  
Z(15,1)64.  
Z(15,2)56.  
Z(15,3)51.  
Z(15,4)46.  
Z(15,5)41.  
Z(15,6)38.  
Z(15,7)36.  
Z(15,8)34.  
Z(15,9)32.  
Z(15,10)30.  
Z(15,11)28.  
Z(15,12)26.  
Z(15,13)24.  
Z(15,14)22.  
Z(15,15)20.  
Z(15,16)18.  
Z(16,1)45.

SLOP2360  
SLOP2370  
SLOP2380  
SLOP2390  
SLOP2400  
SLOP2410  
SLOP2420  
SLOP2430  
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SLOP2460  
SLOP2470  
SLOP2480  
SLOP2490  
SLOP2500  
SLOP2510  
SLOP2520  
SLOP2530  
SLOP2540  
SLOP2550  
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SLOP2590  
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SLOP2690  
SLOP2700  
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SLOP2720  
SLOP2730  
SLOP2740  
SLOP2750  
SLOP2760  
SLOP2770  
SLOP2780  
SLOP2790  
SLOP2800  
SLOP2810  
SLOP2820  
SLOP2830

Z(16,2) 1.  
 Z(16,3) 38.  
 Z(16,4) 35.  
 Z(16,5) 33.  
 Z(16,6) 30.  
 Z(16,7) 28.  
 Z(16,8) 26.  
 Z(16,9) 24.  
 Z(16,10) 22.  
 Z(16,11) 20.  
 Z(16,12) 18.  
 Z(16,13) 16.  
 Z(16,14) 14.  
 Z(16,15) 12.  
 Z(16,16) 10.  
 Z(17,1) 30.  
 Z(17,2) 28.  
 Z(17,3) 26.  
 Z(17,4) 24.  
 Z(17,5) 23.  
 Z(17,6) 22.  
 Z(17,7) 20.  
 Z(17,8) 18.  
 Z(17,9) 16.  
 Z(17,10) 14.  
 Z(17,11) 12.  
 Z(17,12) 10.  
 Z(17,13) 8.  
 Z(17,14) 6.  
 Z(17,15) 4.  
 Z(17,16) 2.  
 Z(18,1) 17.  
 Z(18,2) 17.  
 Z(18,3) 16.  
 Z(18,4) 16.  
 Z(18,5) 16.  
 Z(18,6) 16.  
 Z(18,7) 15.  
 Z(18,8) 15.  
 Z(18,9) 15.  
 Z(18,10) 14.  
 Z(18,11) 14.  
 Z(18,12) 14.  
 Z(18,13) 12.  
 Z(18,14) 12.  
 Z(18,15) 12.  
 Z(18,16) 10.  
 Z(19,1) 6.

S10P2840  
 S10P2850  
 S10P2860  
 S10P2870  
 S10P2880  
 S10P2890  
 S10P2900  
 S10P2910  
 S10P2920  
 S10P2930  
 S10P2940  
 S10P2950  
 S10P2960  
 S10P2970  
 S10P2980  
 S10P2990  
 S10P3000  
 S10P3010  
 S10P3020  
 S10P3030  
 S10P3040  
 S10P3050  
 S10P3060  
 S10P3070  
 S10P3080  
 S10P3090  
 S10P3100  
 S10P3110  
 S10P3120  
 S10P3130  
 S10P3140  
 S10P3150  
 S10P3160  
 S10P3170  
 S10P3180  
 S10P3190  
 S10P3200  
 S10P3210  
 S10P3220  
 S10P3230  
 S10P3240  
 S10P3250  
 S10P3260  
 S10P3270  
 S10P3280  
 S10P3290  
 S10P3300

SL0P3320  
SL0P3330  
SL0P3340  
SL0P3350  
SL0P3360  
SL0P3370  
SL0P3380  
SL0P3390  
SL0P3400  
SL0P3410  
SL0P3420  
SL0P3430  
SL0P3440  
SL0P3450  
SL0P3460  
SL0P3470  
SL0P3480  
SL0P3490  
SL0P3500  
SL0P3510  
SL0P3520  
SL0P3530  
SL0P3540  
SL0P3550  
SL0P3560  
SL0P3570  
SL0P3580  
SL0P3590  
SL0P3600  
SL0P3610  
SL0P3620  
SL0P3630  
SL0P3640  
SL0P3650  
SL0P3660  
SL0P3670  
SL0P3680  
SL0P3690  
SL0P3700  
SL0P3710  
SL0P3720  
SL0P3730  
SL0P3740  
SL0P3750  
SL0P3760  
SL0P3770  
SL0P3780  
SL0P3790

z(19,2)	7.
z(19,3)	7.
z(19,4)	8.
z(19,5)	8.
z(19,6)	9.
z(19,7)	9.
z(19,8)	8.
z(19,9)	7.
z(19,10)	6.
z(19,11)	5.
z(19,12)	4.
z(19,13)	3.
z(19,14)	2.
z(19,15)	0.
z(19,16)	-5.
z(20,1)	-4.
z(20,2)	-3.
z(20,3)	-1.
z(20,4)	0.
z(20,5)	0.
z(20,6)	0.
z(20,7)	0.
z(20,8)	0.
z(20,9)	0.
z(20,10)	0.
z(20,11)	0.
z(20,12)	0.
z(20,13)	0.
z(20,14)	0.
z(20,15)	0.
z(20,16)	0.
z(21,1)	-5.
z(21,2)	-4.
z(21,3)	-1.
z(21,4)	0.
z(21,5)	0.
z(21,6)	0.
z(21,7)	0.
z(21,8)	0.
z(21,9)	0.
z(21,10)	0.
z(21,11)	0.
z(21,12)	0.
z(21,13)	0.
z(21,14)	0.
z(21,15)	0.
z(21,16)	0.
z(22,1)	-6.



W(2,3)  
W(2,4)  
W(2,5)  
W(2,6)  
W(2,7)  
W(2,8)  
W(2,9)  
W(2,10)  
W(2,11)  
W(2,12)  
W(2,13)  
W(2,14)  
W(2,15)  
W(2,16)  
W(3,1)  
W(3,2)  
W(3,3)  
W(3,4)  
W(3,5)  
W(3,6)  
W(3,7)  
W(3,8)  
W(3,9)  
W(3,10)  
W(3,11)  
W(3,12)  
W(3,13)  
W(3,14)  
W(3,15)  
W(3,16)  
W(4,1)  
W(4,2)  
W(4,3)  
W(4,4)  
W(4,5)  
W(4,6)  
W(4,7)  
W(4,8)  
W(4,9)  
W(4,10)  
W(4,11)  
W(4,12)  
W(4,13)  
W(4,14)  
W(4,15)  
W(4,16)  
W(5,1)

= 10.  
= 19.  
= 8.  
= 6.  
= 4.  
= 2.  
= 0.  
= 0.  
= 0.  
= 0.  
= 0.  
= 0.  
= 0.  
= 0.  
= 14.  
= 14.  
= 11.  
= 10.  
= 9.  
= 8.  
= 7.  
= 6.  
= 5.  
= 4.  
= 3.  
= 2.  
= 1.  
= 0.  
= 0.  
= 0.  
= 14.  
= 12.  
= 10.  
= 8.  
= 7.  
= 6.  
= 5.  
= 4.  
= 3.  
= 2.  
= 1.  
= 0.  
= 0.  
= 0.  
= 7.

SLOP4280  
SLOP4290  
SLOP4300  
SLOP4310  
SLOP4320  
SLOP4330  
SLOP4340  
SLOP4350  
SLOP4360  
SLOP4370  
SLOP4380  
SLOP4390  
SLOP4400  
SLOP4410  
SLOP4420  
SLOP4430  
SLOP4440  
SLOP4450  
SLOP4460  
SLOP4470  
SLOP4480  
SLOP4490  
SLOP4500  
SLOP4510  
SLOP4520  
SLOP4530  
SLOP4540  
SLOP4550  
SLOP4560  
SLOP4570  
SLOP4580  
SLOP4590  
SLOP4600  
SLOP4610  
SLOP4620  
SLOP4630  
SLOP4640  
SLOP4650  
SLOP4660  
SLOP4670  
SLOP4680  
SLOP4690  
SLOP4700  
SLOP4710  
SLOP4720  
SLOP4730  
SLOP4740  
SLOP4750

W(5,2)	6.	=	5.
W(5,3)	5.	=	4.
W(5,4)	4.	=	3.
W(5,5)	3.	=	2.
W(5,6)	2.	=	1.
W(5,7)	1.	=	0.
W(5,8)	0.	=	0.
W(5,9)	0.	=	0.
W(5,10)	0.	=	0.
W(5,11)	0.	=	0.
W(5,12)	0.	=	0.
W(5,13)	0.	=	0.
W(5,14)	0.	=	0.
W(5,15)	0.	=	0.
W(5,16)	0.	=	0.
W(6,1)	-5.	=	-5.
W(6,2)	-5.	=	-4.
W(6,3)	-4.	=	-4.
W(6,4)	-4.	=	-4.
W(6,5)	-4.	=	-4.
W(6,6)	-4.	=	-3.
W(6,7)	-3.	=	-3.
W(6,8)	-3.	=	-2.
W(6,9)	-2.	=	-2.
W(6,10)	-2.	=	-1.
W(6,11)	-1.	=	-1.
W(6,12)	-1.	=	0.
W(6,13)	0.	=	0.
W(6,14)	0.	=	0.
W(6,15)	0.	=	0.
W(6,16)	0.	=	0.
W(7,1)	-18.	=	-16.
W(7,2)	-16.	=	-14.
W(7,3)	-14.	=	-12.
W(7,4)	-12.	=	-10.
W(7,5)	-10.	=	-9.
W(7,6)	-9.	=	-8.
W(7,7)	-8.	=	-7.
W(7,8)	-7.	=	-6.
W(7,9)	-6.	=	-5.
W(7,10)	-5.	=	-4.
W(7,11)	-4.	=	-3.
W(7,12)	-3.	=	-2.
W(7,13)	-2.	=	-1.
W(7,14)	-1.	=	0.
W(7,15)	0.	=	0.
W(7,16)	0.	=	0.
W(8,1)	-30.	=	-30.

SLOP4760	SLOP4770
SLOP4780	SLOP4790
SLOP4800	SLOP4810
SLOP4820	SLOP4830
SLOP4840	SLOP4850
SLOP4860	SLOP4870
SLOP4880	SLOP4890
SLOP4900	SLOP4910
SLOP4920	SLOP4930
SLOP4940	SLOP4950
SLOP4960	SLOP4970
SLOP4980	SLOP4990
SLOP5000	SLOP5010
SLOP5020	SLOP5030
SLOP5040	SLOP5050
SLOP5060	SLOP5070
SLOP5080	SLOP5090
SLOP5100	SLOP5110
SLOP5120	SLOP5130
SLOP5140	SLOP5150
SLOP5160	SLOP5170
SLOP5180	SLOP5190
SLOP5200	SLOP5210
SLOP5220	SLOP5230

W(8,2)	26.
W(8,3)	-22.
W(8,4)	-19.
W(8,5)	-17.
W(8,6)	-15.
W(8,7)	-13.
W(8,8)	-11.
W(8,9)	-9.
W(8,10)	-7.
W(8,11)	-5.
W(8,12)	-3.
W(8,13)	-1.
W(8,14)	0.
W(8,15)	0.
W(8,16)	0.
W(9,1)	-4.
W(9,2)	-3.
W(9,3)	-3.
W(9,4)	-2.
W(9,5)	-2.
W(9,6)	-1.
W(9,7)	-1.
W(9,8)	-1.
W(9,9)	-1.
W(9,10)	-1.
W(9,11)	-1.
W(9,12)	-1.
W(9,13)	-1.
W(9,14)	-1.
W(9,15)	-1.
W(9,16)	-1.
W(10,1)	-4.
W(10,2)	-3.
W(10,3)	-3.
W(10,4)	-2.
W(10,5)	-2.
W(10,6)	-2.
W(10,7)	-1.
W(10,8)	-1.
W(10,9)	-1.
W(10,10)	-1.
W(10,11)	-1.
W(10,12)	-1.
W(10,13)	-1.
W(10,14)	-1.
W(10,15)	-1.
W(10,16)	-1.
W(11,1)	-4.

S	OP	52	40
S	OP	52	50
S	OP	52	60
S	OP	52	70
S	OP	52	80
S	OP	52	90
S	OP	53	00
S	OP	53	10
S	OP	53	20
S	OP	53	30
S	OP	53	40
S	OP	53	50
S	OP	53	60
S	OP	53	70
S	OP	53	80
S	OP	53	90
S	OP	54	00
S	OP	54	10
S	OP	54	20
S	OP	54	30
S	OP	54	40
S	OP	54	50
S	OP	54	60
S	OP	54	70
S	OP	54	80
S	OP	54	90
S	OP	55	00
S	OP	55	10
S	OP	55	20
S	OP	55	30
S	OP	55	40
S	OP	55	50
S	OP	55	60
S	OP	55	70
S	OP	55	80
S	OP	55	90
S	OP	56	00
S	OP	56	10
S	OP	56	20
S	OP	56	30
S	OP	56	40
S	OP	56	50
S	OP	56	60
S	OP	56	70
S	OP	56	80
S	OP	56	90
S	OP	57	00
S	OP	57	10

W(11,1,1) 37.  
W(11,1,2) -33.  
W(11,1,3) -28.  
W(11,1,4) -25.  
W(11,1,5) -20.  
W(11,1,6) -17.  
W(11,1,7) -14.  
W(11,1,8) -11.  
W(11,1,9) -9.  
W(11,1,10) -7.  
W(11,1,11) -5.  
W(11,1,12) -3.  
W(11,1,13) -2.  
W(11,1,14) -1.  
W(11,1,15) 0.  
W(11,1,16) 37.  
W(12,2,1) -33.  
W(12,2,2) -30.  
W(12,2,3) -26.  
W(12,2,4) -23.  
W(12,2,5) -20.  
W(12,2,6) -17.  
W(12,2,7) -14.  
W(12,2,8) -11.  
W(12,2,9) -9.  
W(12,2,10) -7.  
W(12,2,11) -5.  
W(12,2,12) -3.  
W(12,2,13) -2.  
W(12,2,14) -1.  
W(12,2,15) 0.  
W(12,2,16) 29.  
W(13,3,1) -26.  
W(13,3,2) -25.  
W(13,3,3) -22.  
W(13,3,4) -19.  
W(13,3,5) -17.  
W(13,3,6) -15.  
W(13,3,7) -13.  
W(13,3,8) -11.  
W(13,3,9) -9.  
W(13,3,10) -7.  
W(13,3,11) -5.  
W(13,3,12) -3.  
W(13,3,13) -2.  
W(13,3,14) -1.  
W(13,3,15) 0.  
W(13,3,16) 18.  
W(14,4,1) -18.

SLOP5720  
SLOP5730  
SLOP5740  
SLOP5750  
SLOP5760  
SLOP5770  
SLOP5780  
SLOP5790  
SLOP5800  
SLOP5810  
SLOP5820  
SLOP5830  
SLOP5840  
SLOP5850  
SLOP5860  
SLOP5870  
SLOP5880  
SLOP5890  
SLOP5900  
SLOP5910  
SLOP5920  
SLOP5930  
SLOP5940  
SLOP5950  
SLOP5960  
SLOP5970  
SLOP5980  
SLOP5990  
SLOP6000  
SLOP6010  
SLOP6020  
SLOP6030  
SLOP6040  
SLOP6050  
SLOP6060  
SLOP6070  
SLOP6080  
SLOP6090  
SLOP6100  
SLOP6110  
SLOP6120  
SLOP6130  
SLOP6140  
SLOP6150  
SLOP6160  
SLOP6170  
SLOP6180  
SLOP6190

[illegible]



SSLOP7160  
SSLOP7170  
SSLOP7180  
SSLOP7190  
SSLOP7200  
SSLOP7210  
SSLOP7220  
SSLOP7230  
SSLOP7240  
SSLOP7250  
SSLOP7260  
SSLOP7270  
SSLOP7280  
SSLOP7290  
SSLOP7300  
SSLOP7310  
SSLOP7320  
SSLOP7330  
SSLOP7340  
SSLOP7350  
SSLOP7360  
SSLOP7370  
SSLOP7380  
SSLOP7390  
SSLOP7400  
SSLOP7410  
SSLOP7420  
SSLOP7430  
SSLOP7440  
SSLOP7450  
SSLOP7460  
SSLOP7470  
SSLOP7480  
SSLOP7490  
SSLOP7500  
SSLOP7510  
SSLOP7520  
SSLOP7530  
SSLOP7540  
SSLOP7550  
SSLOP7560  
SSLOP7570  
SSLOP7580  
SSLOP7590  
SSLOP7600  
SSLOP7610  
SSLOP7620  
SSLOP7630

WW(20,2)10.  
WW(20,3)19.  
WW(20,4)8.  
WW(20,5)7.  
WW(20,6)7.  
WW(20,7)6.  
WW(20,8)5.  
WW(20,9)4.  
WW(20,10)3.  
WW(20,11)2.  
WW(20,12)1.  
WW(20,13)0.  
WW(20,14)0.  
WW(20,15)0.  
WW(20,16)0.  
WW(21,1)10.  
WW(21,2)9.  
WW(21,3)7.  
WW(21,4)6.  
WW(21,5)5.  
WW(21,6)4.  
WW(21,7)3.  
WW(21,8)2.  
WW(21,9)1.  
WW(21,10)0.  
WW(21,11)0.  
WW(21,12)0.  
WW(21,13)0.  
WW(21,14)0.  
WW(21,15)0.  
WW(21,16)0.  
WW(22,1)5.  
WW(22,2)4.  
WW(22,3)3.  
WW(22,4)3.  
WW(22,5)2.  
WW(22,6)2.  
WW(22,7)1.  
WW(22,8)1.  
WW(22,9)0.  
WW(22,10)0.  
WW(22,11)0.  
WW(22,12)0.  
WW(22,13)0.  
WW(22,14)0.  
WW(22,15)0.  
WW(22,16)0.  
WW(23,1)0.

SLOP7640  
 SLOP7650  
 SLOP7660  
 SLOP7670  
 SLOP7680  
 SLOP7690  
 SLOP7700  
 SLOP7710  
 SLOP7720  
 SLOP7730  
 SLOP7740  
 SLOP7750  
 SLOP7760  
 SLOP7770  
 SLOP7780  
 SLOP7790  
 SLOP7800  
 SLOP7810  
 SLOP7820  
 SLOP7830  
 SLOP7840  
 SLOP7850  
 SLOP7860  
 SLOP7870  
 SLOP7880  
 SLOP7890  
 SLOP7900  
 SLOP7910  
 SLOP7920  
 SLOP7930  
 SLOP7940  
 SLOP7950  
 SLOP7960  
 SLOP7970  
 SLOP7980  
 SLOP7990  
 SLOP8000  
 SLOP8010  
 SLOP8020  
 SLOP8030  
 SLOP8040  
 SLOP8050  
 SLOP8060  
 SLOP8070  
 SLOP8080  
 SLOP8090  
 SLOP8100  
 SLOP8110

```

W(23,2) = 0.
W(23,3) = 0.
W(23,4) = 0.
W(23,5) = 0.
W(23,6) = 0.
W(23,7) = 0.
W(23,8) = 0.
W(23,9) = 0.
W(23,10) = 0.
W(23,11) = 0.
W(23,12) = 0.
W(23,13) = 0.
W(23,14) = 0.
W(23,15) = 0.
W(23,16) = 0.
IF (ABS(DY).GE..4734) GO TO 1
IF (ABS(DX).GT.1.15) GO TO 1
I = IFIX((DX+1.1002)/.1)+1.
J = (J.LT.1) J = 1
IF (I.LT.1) I = 1
IF (I.GT.23) I = 23
IF (J.GT.16) J = 16
K = 24-I
DELX = DX-X(I)
DELY = ABS(DY)-Y(J)
DELK = DX-X(K)
IF ((I.EQ.23) OR (J.EQ.16)) GO TO 2
DYD1 = DELX*(Z(I+1,J))-Z(I,J))+DELY*(Z(I,J+1))-Z(I,J))
DYD2 = DELK*(Z(K+1,J))-Z(K,J))+DELY*(Z(K,J+1))-Z(K,J))
DYND1 = DELX*(W(I+1,J))-W(I,J))+DELY*(W(I,J+1))-W(I,J))
DYND2 = DELK*(W(K+1,J))-W(K,J))+DELY*(W(K,J+1))-W(K,J))
YY1 = (Z(I,J)+DYD1)*1.E-05
YY2 = -(Z(K,J)+DYD2)*1.E-05
YN1 = (W(I,J)+DYND1)*1.E-05
YN2 = -(W(K,J)+DYND2)*1.E-05
IF (DY.LT.0.) GO TO 3
RETURN
1 YY1 = 0.
  YY2 = 0.
  YN1 = 0.
  YN2 = 0.
RETURN
2 YY1 = Z(I,J)*1.E-05
  YY2 = -Z(K,J)*1.E-05
  YN1 = W(I,J)*1.E-05
  YN2 = -W(K,J)*1.E-05
  IF (DY.LT.0.) GO TO 3
  
```

SLOP8120  
SLOP8130  
SLOP8140  
SLOP8150  
SLOP8160  
SLOP8170  
SLOP8180

3  
RETURN -YY1  
YY1 = -YY2  
YY2 = -YN1  
YN1 = -YN2  
YN2 = -RETURN  
RETURN  
END

## FUNCTION SPINIT

This function was designed to aid in initialization problems associated with the DSL function DELY. The effect is that the function initializes the delay loop until it can be self-supportive.

FUNCTION SPINIT

```
FUNCTION SPINIT (SPDDEL, TIME, SPD0)  
IF (TIME.GT.0.5) GO TO 1  
SPINIT = SPD0  
RETURN  
1 SPINIT = SPDDEL  
RETURN  
END
```

```
SPIN 10  
SPIN 20  
SPIN 30  
SPIN 40  
SPIN 50  
SPIN 60  
SPIN 70
```

## FUNCTION SPDCTR

This function is the speed control used during heading control development. It is used directly as the speed of the control ship with information of the speed of the two ships and the longitudinal position ADX. It contains a linear function at  $\pm 1.0$  ship lengths to a dead zone of  $\pm 0.001$  centered about the alongside position (0.0).

FUNCTION SPDCTR

```
FUNCTION SPDCTR (ADX,U01,U02)
  IF (ADX.LT.-1.0) GO TO 1
  IF (ADX.GT.1.0) GO TO 2
  IF (ABS(ADX).LT.0.001) GO TO 3
  SPDCTR = -ADX*(U02-U01)+U01
  RETURN
1 SPDCTR = U02
2 RETURN = U02-U01
3 RETURN = U01
END
```

SPCR 10  
SPCR 20  
SPCR 30  
SPCR 40  
SPCR 50  
SPCR 60  
SPCR 70  
SPCR 80  
SPCR 90  
SPCR 100  
SPCR 110  
SPCR 120  
SPCR 130

## FUNCTION SPDOFC

This function is identical to SPDREC except that the ability to offset the alongside position (0.0) is incorporated. This is the speed control function in its final development form.

# FUNCTION SPD0FC

```

FUNCTION SPD0FC (ADX, SPD01, SPD02, SW, XOFS)
SWTCH = -SW*(SPD02-SPD01)
IF ((ADX-XOFS).LT.SWTCH) GO TO 1
IF ((ADX-XOFS).GT.-SWTCH) GO TO 2
IF (ABS(ADX-XOFS).LT.0.001) GO TO 3
SPD0FC = -(ADX-XOFS)*(SPD02-SPD01)+SPD01
RETURN
1 SPD0FC = SPD02
2 SPD0FC = SPD02-SPD01
3 SPD0FC = SPD01
END

```

```

SPD00 10
SPD00 20
SPD00 30
SPD00 40
SPD00 50
SPD00 60
SPD00 70
SPD00 80
SPD00 90
SPD00 100
SPD00 110
SPD00 120
SPD00 130
SPD00 140

```

## FUNCTION SPDREC

This function is similar to SPDCTR except that a switching function is incorporated. This is the function used for optimization of the switching function and is used in the velocity loop simulated in the velocity control section of chapter III.

FUNCTION SPDREC

```
FUNCTION SPDREC (ADX,SPD01,SPD02,SW)
SWITCH = -SW*(SPD02-SPD01)
IF (ADX.LT.SWITCH) GO TO 1
IF (ADX.GT.-SWITCH) GO TO 2
IF (ABS(ADX).LT.0.001) GO TO 3
SPDREC = -ADX*(SPD02-SPD01)+SPD01
RETURN
1 SPDREC = SPD02
2 SPDREC = SPD02-SPD01
3 SPDREC = SPD01
END
```

SPDR 10  
SPDR 20  
SPDR 30  
SPDR 40  
SPDR 50  
SPDR 60  
SPDR 70  
SPDR 80  
SPDR 90  
SPDR 100  
SPDR 110  
SPDR 120  
SPDR 130  
SPDR 140

## FUNCTION SWCL

This function contains the fifth order polynomial curve fit for the optimal switching position of the speed control loop. Its range of values for SPDDIF are 0.1 to 1.0 normalized speed difference between the two ships.

FUNCTION SWCL

FUNCTION SWCL (SPD01, SPD02)  
SPDDIF = SPD02-SPD01  
SWCL = -2.24869\*SPDDIF\*\*5+6.93243\*SPDDIF\*\*4-8.04233\*SPDDIF\*\*3+4.08  
1065\*SPDDIF\*\*2-0.409977\*SPDDIF+0.554  
RETURN  
END

SWCL  
SWCL  
SWCL  
SWCL  
SWCL  
SWCL

10  
20  
30  
40  
50  
60

## SUBROUTINE SWITCH

This subroutine contains the gains and mechanisms required for the adaptive gain schedule developed in this thesis. It includes the optimal gains obtained from the heading control optimization runs.

# SUBROUTINE SWITCH

```

C
SUBROUTINE SWITCH (DD,DA,AA1,IS,RSENS,WTSENS,RGN,VFBG,BDOT2D)
SUBROUTINE TO SWITCH RAS GAINS ONCE SHIPS ALONGSIDE
DDC = DD
IF (IS.EQ.0) DDC = -DD
AMDY = DDC+DA*SIN(AA1)
AMDX = DA*COS(AA1)
IF (ABS(AMDX).GT.1.0) N=1
IF (ABS(AMDX).LT.0.5.AND.ABS(AMDY).LT.0.005) GO TO 1
IF (ABS(AMDY).LT.0.05) GO TO 2
N = 1
RSENS = 1.86642
WTSENS = 2.38692
RGN = 23.41847
VFBG = 4.35162
RETURN
1 RSENS = 1.99765
WTSENS = 0.7357
RGN = 49.97757
VFBG = 0.084028
N = N+1
IF (ABS(BDOT2D).GT.2.0.AND.N.LT.150) VFBG=1.0
RETURN
2 RSENS = 4.0
WTSENS = 2.38692
RGN = 23.41847
VFBG = 4.35162
IF (N.GT.150) GO TO 1
N = 1
RETURN
END
SWITH 10
SWITH 20
SWITH 30
SWITH 40
SWITH 50
SWITH 60
SWITH 70
SWITH 80
SWITH 90
SWITH 100
SWITH 110
SWITH 120
SWITH 130
SWITH 140
SWITH 150
SWITH 160
SWITH 170
SWITH 180
SWITH 190
SWITH 200
SWITH 210
SWITH 220
SWITH 230
SWITH 240
SWITH 250
SWITH 260
SWITH 270
SWITH 280
SWITH 290
SWITH 300

```

## SUBROUTINE SWTCHF

This subroutine is identical to SWTCH except that the turn phase gain VFEG is relaxed to allow for offset longitudinal position placement. This is the adaptive gain schedule in its final form.

# SUBROUTINE SWITCHF

```

SUBROUTINE SWITCHF (DD,DA,AA1,IS,RSENS,WTSENS,RGN,VFBG,BDOT2D,XOFS)
SUBROUTINE TO SWITCH RAS GAINS ONCE SHIPS ALONGSIDE
DDC = DD
IF (IS.EQ.0) DDC = -DD
AMDY = DDC+DA*SIN(AA1)
AMDY = DA*COS(AA1)
IF (ABS(AMDY-XOFS).GT.1.0) N=1
IF (ABS(AMDY).LT.0.05) GO TO 2
N = 1
RSENS = 1.86642
WTSENS = 2.38692
RGN = 23.41847
VFBG = 4.35162
RETURN
1 RSENS = 1.99765
WTSENS = 0.7357
RGN = 49.97757
VFBG = 0.1
IF (ABS(BDOT2D).GT.2.0.AND.N.LE.150) VFBG=1.0
N = N+1
RETURN
2 RSENS = 4.0
WTSENS = 2.38692
RGN = 23.41847
VFBG = 4.35162
IF (N.GT.150) GO TO 1
N = 1
RETURN
END

```

10 SWITCHF  
 20 SWITCHF  
 30 SWITCHF  
 40 SWITCHF  
 50 SWITCHF  
 60 SWITCHF  
 70 SWITCHF  
 80 SWITCHF  
 90 SWITCHF  
 100 SWITCHF  
 110 SWITCHF  
 120 SWITCHF  
 130 SWITCHF  
 140 SWITCHF  
 150 SWITCHF  
 160 SWITCHF  
 170 SWITCHF  
 180 SWITCHF  
 190 SWITCHF  
 200 SWITCHF  
 210 SWITCHF  
 220 SWITCHF  
 230 SWITCHF  
 240 SWITCHF  
 250 SWITCHF  
 260 SWITCHF  
 270 SWITCHF  
 280 SWITCHF  
 290 SWITCHF  
 300 SWITCHF

## SUBROUTINE TRANS

This subrountine takes the lateral and longitudinal geographic displacements and converts them to actual displacements referenced to the control ship's head. This is done to gain a more realistic reference for subrcutine FEMEAS, subrcutine SLOPES, function SPDCTR, function SPDCFC, and function SPDREC.

# SUBROUTINE TRANS

```

SUBROUTINE TRANS (PSIA,DX,DY,ADX,ADY)
  DXY = SQRT(DX**2+DY**2)
  AXY = ARSIN(-DY/DXY)
  IF (DX.LT.0.) AXY = 3.141592654-AXY
  AT = AXY+PSIA
  ADY = -DXY*SIN(AT)
  ADX = +DXY*COS(AT)
  RETURN
END

```

```

10
20
30
40
50
60
70
80
90
TRNS
TRNS
TRNS
TRNS
TRNS
TRNS
TRNS
TRNS

```

## FUNCTION XLIMIT

This function was developed to allow the LIMIT function of DSL to be incorporated in the optimization runs. It is a saturation amplifier with a gain of 1.0, and upper limit of UL, and a lower limit of XLL.

FUNCTION XLIMIT

```
FUNCTION XLIMIT (XLL,UL,FUNCT)
  FUNCU = FUNCT
  IF (FUNCT.LT.XLL) FUNCU=XLL
  IF (FUNCT.GT.UL) FUNCU=UL
  XLIMIT = FUNCU
  RETURN
END
```

```
XLMT 10
XLMT 20
XLMT 30
XLMT 40
XLMT 50
XLMT 60
XLMT 70
```

## APPENDIX B

The final form of the simulation program, with all its subroutines and functions, is a very complex and complicated maze. To aid in following its progression, this appendix contains a detailed block diagram of the program with each variable listed in its computer variable name. Each page contains a functional part of the simulation with inputs and outputs shown cross referenced to their origin and destination.

The following is a list of the block diagrams contained in this appendix in the order in which they appear:

- Ship A (Reference Ship) Simulation

  - Ship A Heading Simulation

  - Ship A Speed Simulation

- Ship B (Control Ship) Simulation

  - Ship B Heading Simulation

  - Ship B Speed Simulation

- Subroutine RBMEAS

  - Range Measurement

  - Bearing Measurement

- Subroutine HDGRAS

  - Heading Control Loop

- Auxiliary Functions

  - Yaw Conversion

  - Coordinate Conversion

  - Feedback Loop

- Rudder Modeling

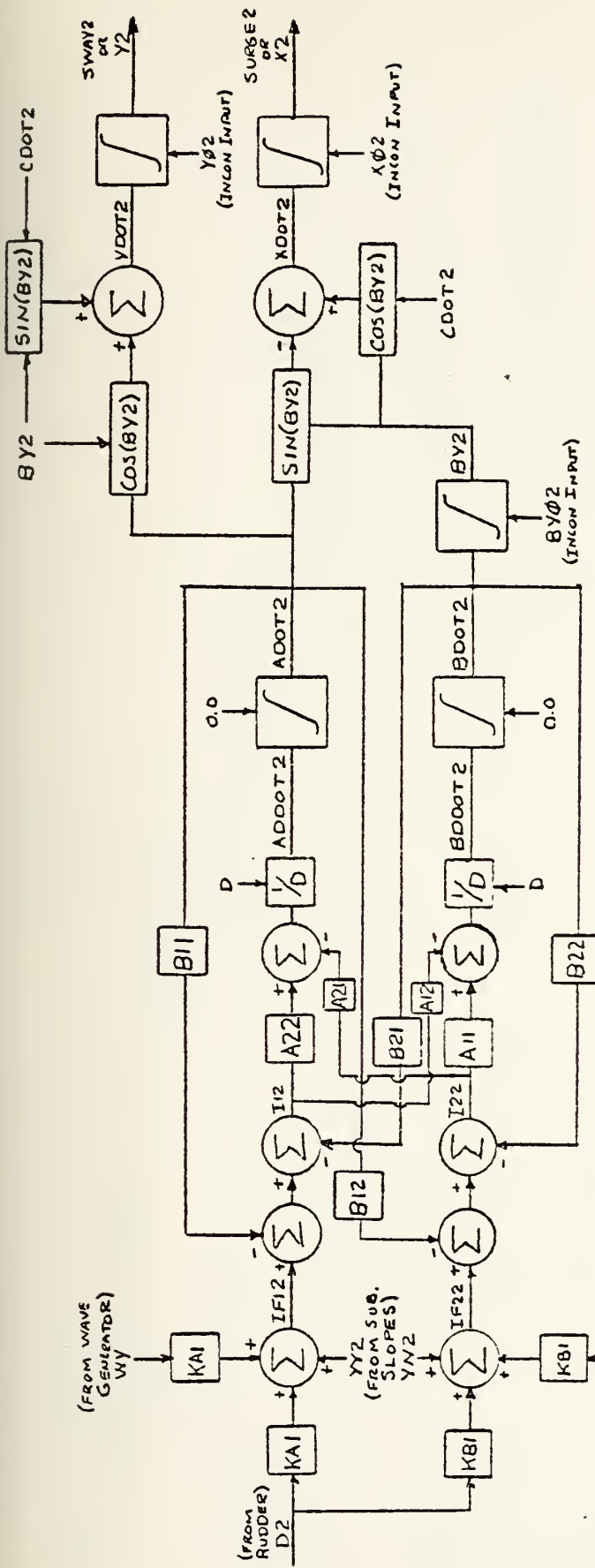
  - Ship A Rudder

  - Ship B Rudder

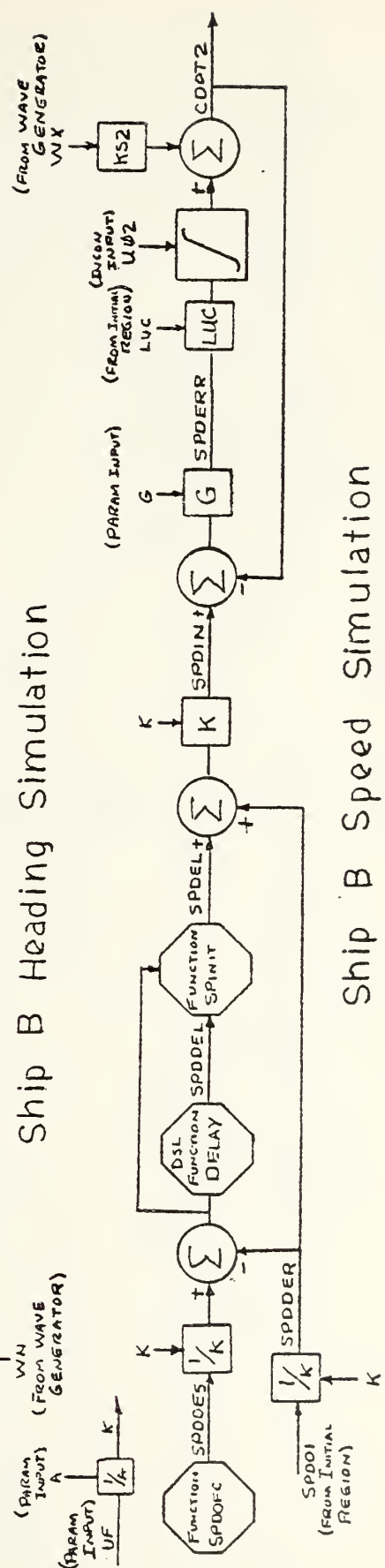
- Wave Generator

Wave Direction  
Random Variable  
Wave Encounter  
Wave Components



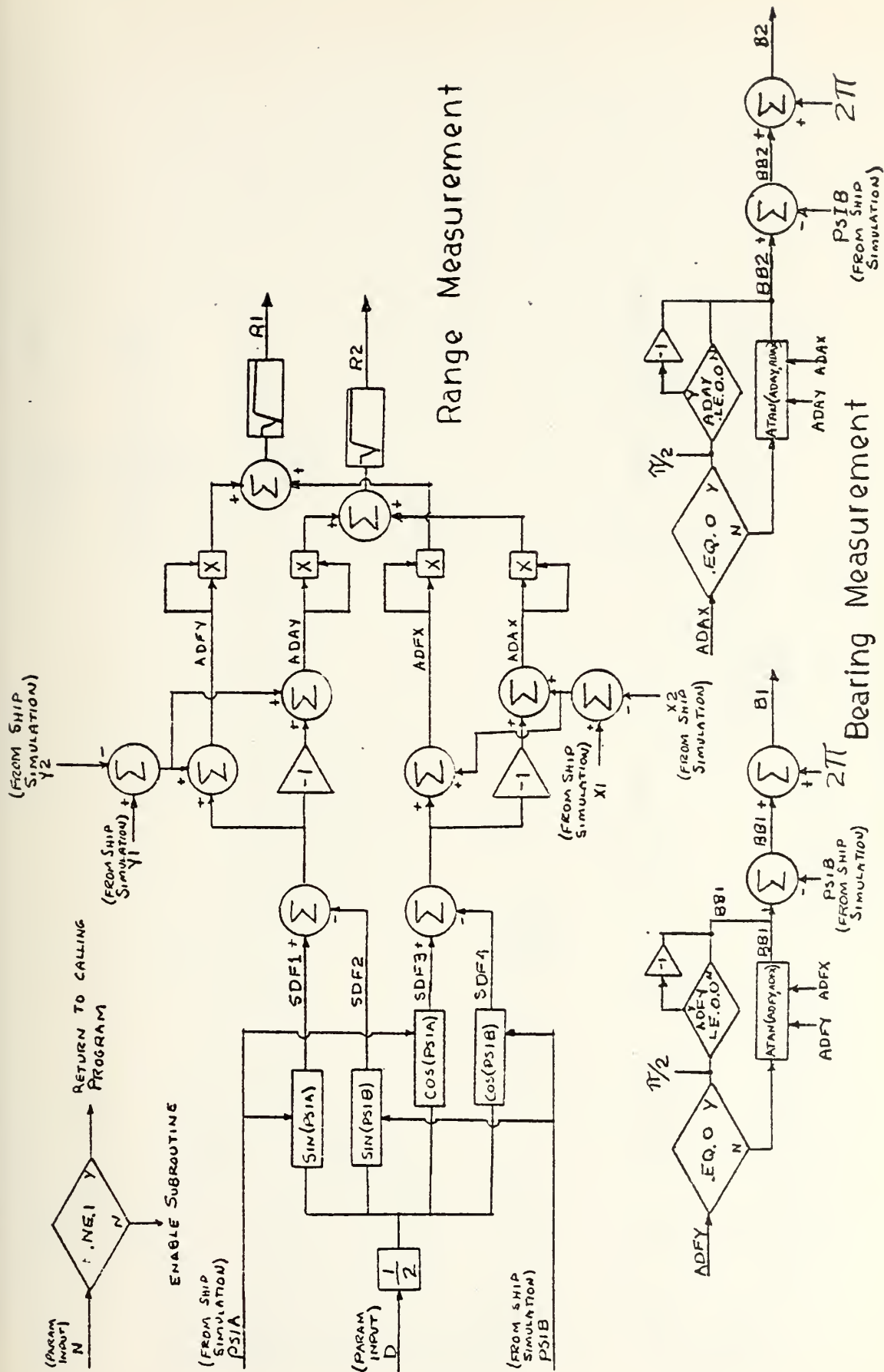


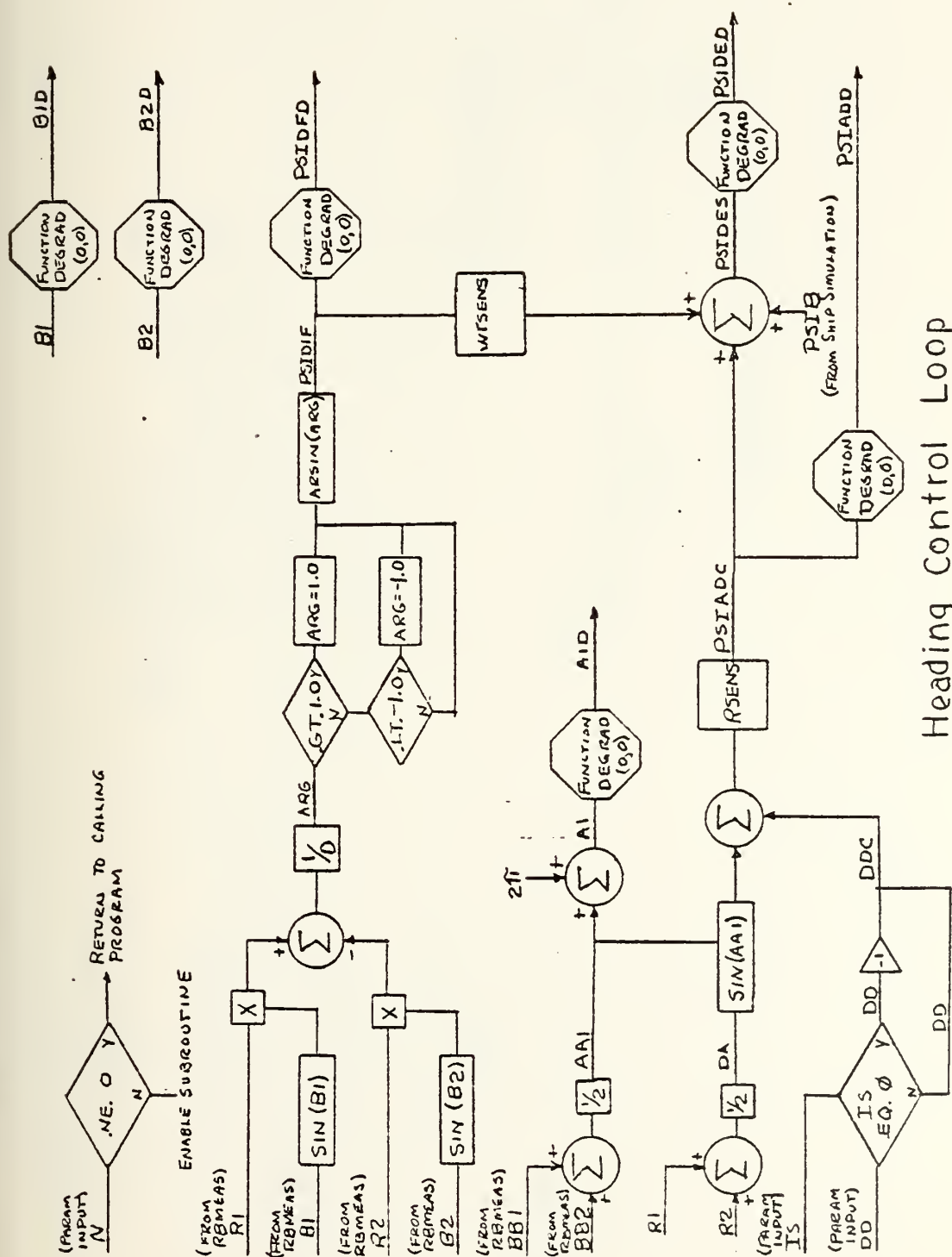
## Ship B Heading Simulation



## Ship B Speed Simulation

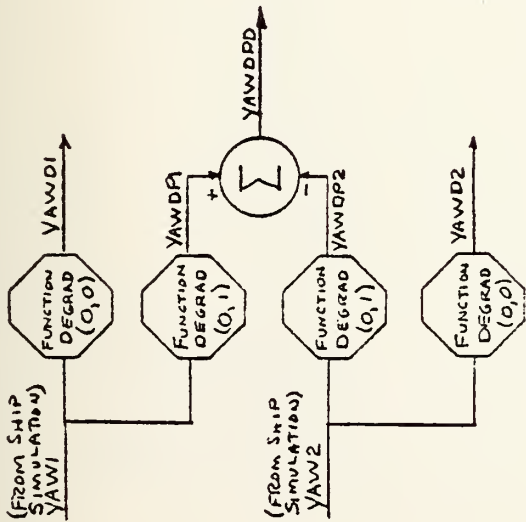
Ship B (Control Ship) Simulation



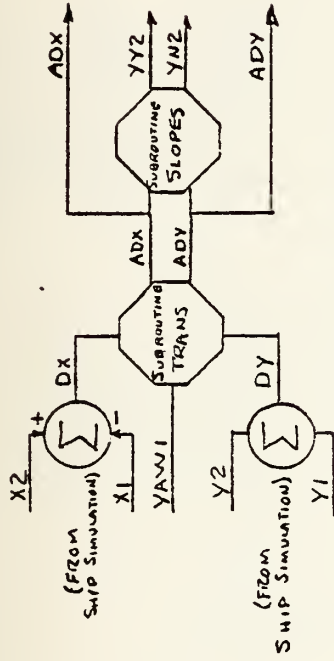


## Heading Control Loop

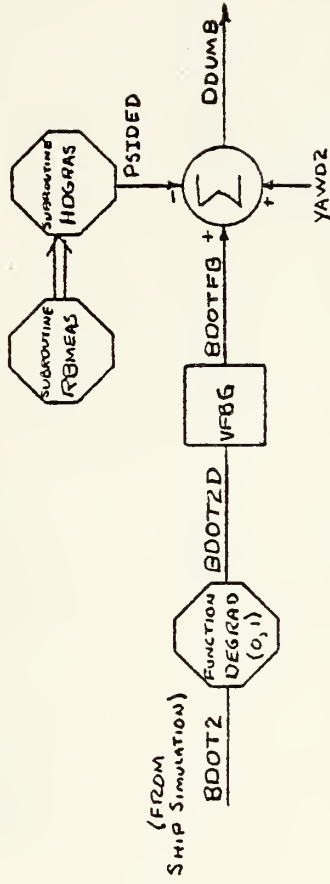
Subroutine HDGRAS



## Yaw conversions

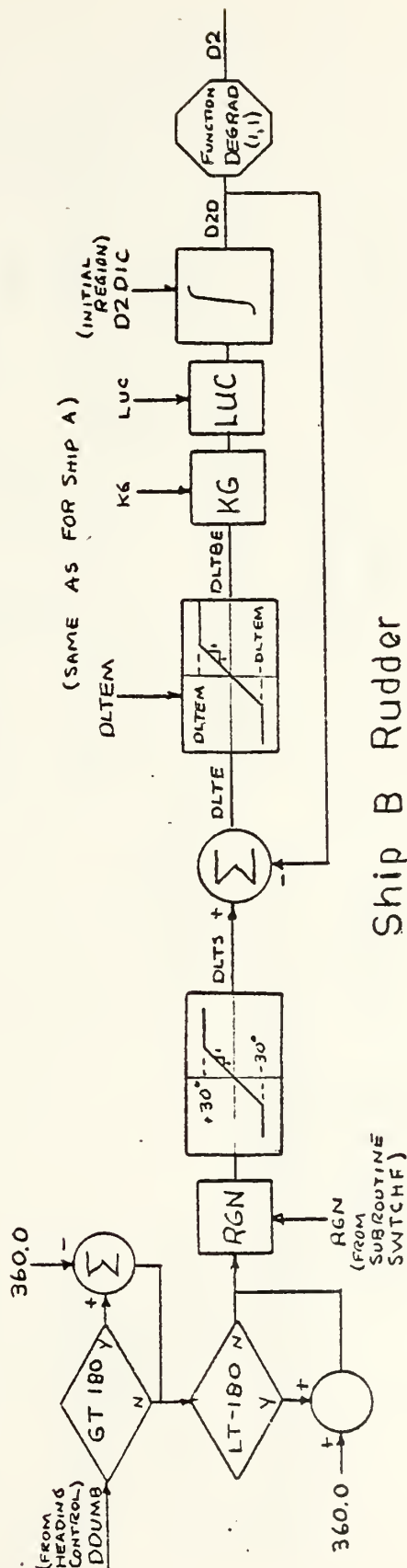
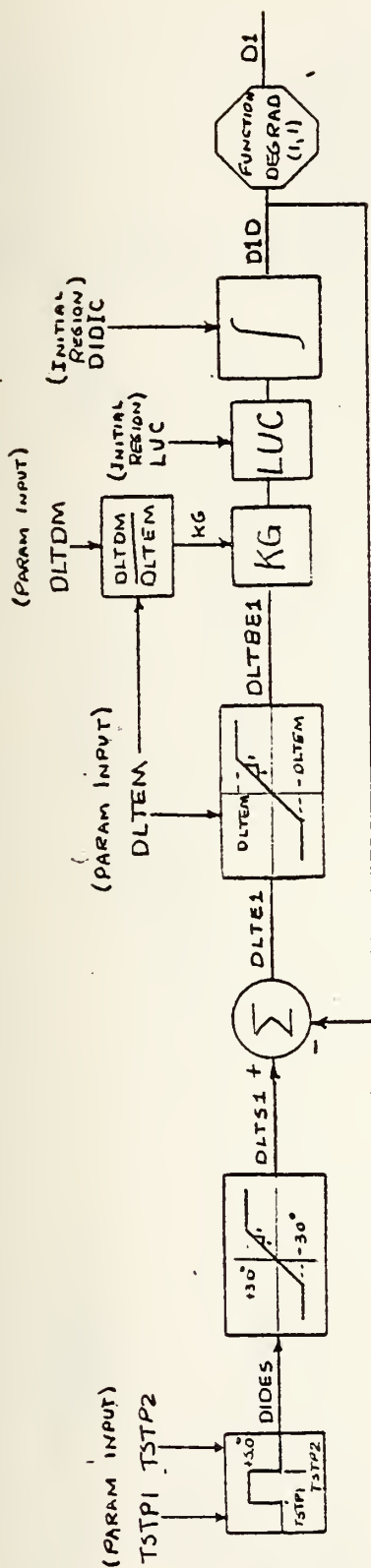


## Coordinate Conversion

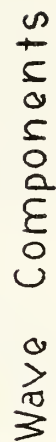
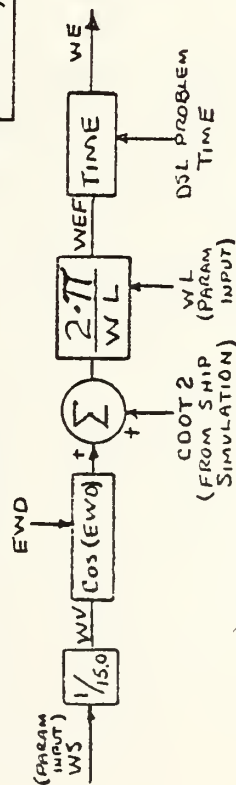
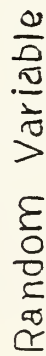
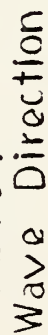


## Feedback Loop

## Auxiliary Functions



## Rudder Modeling



## Wave Encounter

# Wave Generator

## APPENDIX C

Throughout this thesis subroutine SLOPES has been used to output the interactive forces and moments between ships in the RAS situation. This subroutine, adapted from ref. 11, does not contain a complete picture of the circumstances envisioned. In particular, ship's speeds other than the 15 kt. operating point and different ship lengths are not accounted for.

As stated in chapter II, the speed modification factor can easily be applied for both ships at the same speed and other than 15 kts. with the following expression:

$$SPDP = CDOT^2$$

Ships replenishing with different lengths can also be incorporated as shown in ref. 1.

Subroutine FAMIC listed in this appendix incorporates these two ideas along with a better method of determining the interactive forces and moments. The curves of figures II-11 and II-12 were quantized every 50 feet of DX for all the DY curves shown. These points were then used in the NFGS XDS-930C digital computer and AGT-10 graphics terminal to obtain a family of best fit curves. The best fit criteria is based on the sum of the error squared at each quantized point (modified somewhat by this researcher's evaluation of best fit between points to eliminate spikes and other anomalies). The results of this curve fit process is summarized in tables C-1 and C-2, which includes tabulation of the best fit criteria. These polynomial coefficients are based on the DX distance and are coded in

Power	Y50 [YY(1)]	Y60 [YY(2)]	Y70 [YY(3)]	Y80 [YY(4)]	Y90 [YY(5)]	Y100 [YY(6)]
0	84.324	75.260	67.668	59.223	53.449	47.441
1	.364580E 2	.384289E 2	.305160E 2	.221400E 2	.174604E 2	.115702E 2
2	-.118950E 3	-.116865E 3	-.103683E 3	-.944770E 2	-.740983E 2	-.587039E 2
3	-.197311E 2	-.504085E 2	-.265717E 2	-.710687E 1	-.885819E 0	.165712E 2
4	.513437E 2	.684302E 2	.719316E 2	.103147E 3	.467865E 2	.242239E 2
5	.503561E 1	.466749E 2	.158656E 2	-.286063E 1	-.749374E 1	-.397052E 2
6	-.100337E 2	-.194633E 2	-.344841E 2	-.106332E 3	-.206166E 2	-.164427E 1
7	-.484175E 0	-.238722E 2	-.532674E 1	-.304098E 0	.488631E 1	.345891E 2
8	.750949E 0	-.398443E 0	.101864E 2	.688338E 2	.584863E 1	.677233E 0
9		.655075E 1	.877360E 0	.456701E 1	-.136413E 1	-.158999E 2
10		.181994E 1	-.158465E 1	-.221987E 2	-.941379E 0	-.255071E 1
11		-.916189E 0	-.556587E-1	-.347210E 1	.178935E 0	.405863E 1
12		-.428170E 0	.984583E-1	.160105E 1	.729225E-1	.131265E 1
13		.514317E-1		.114485E 1	-.901537E-2	-.543239E 0
14		.316613E-1		.965145E 0	-.176277E-2	-.256741E 0
15				-.179844E 0		.296983E-1
16				-.256001E 0		.177684E-1
17				.109745E-1		
18				.189745E-1		

Table C-1  
Interactive Curve Fit Polynomial Coefficients

Power	Y110[YY(7)]	Y120[YY(8)]	Y130[YY(9)]	Y140[YY(10)]	Y150[YY(11)]
0	40.423	35.484	30.606	26.063	22.876
1	.142822E 2	.146142E 2	.138458E 2	.120761E 2	.108418E 2
2	-.533075E 2	-.458814E 2	-.425663E 2	-.341076E 2	-.196219E 2
3	-.103692E 2	-.158329E 2	-.139724E 2	-.150249E 2	-.127593E 2
4	.389319E 2	.398457E 2	.661640E 2	.574245E 2	.133189E 2
5	.875165E 1	.163639E 2	.863816E 1	.122510E 2	.974262E 1
6	-.200712E 2	-.242537E 2	-.800393E 2	-.702577E 2	-.695905E 1
7	-.502212E 1	-.953711E 1	-.274913E 1	-.333288E 1	-.335866E 1
8	.615393E 1	.820245E 1	.533407E 2	.488103E 2	.214837E 1
9	.154525E 1	.291771E 1	.211749E 1	-.946233E 0	.453764E 0
10	-.972521E 0	-.137319E 1	-.175113E 2	-.195409E 2	-.339142E 0
11	-.237633E 0	-.447954E 0	-.190223E 1	.766196E 0	.407256E-3
12	.607427E-1	.890809E-1	.163223E 1	.448663E 1	.211973E-1
13	.144010E-1	.272508E-1	.777504E 0	-.162184E 0	-.347399E-2
14			.560018E 0	-.548550E 0	
15			-.141969E 0	.116108E-1	
16			-.160683E 0	.276591E-1	
17			.960782E-2		
18			.120067E-1		

Table C-1  
Interactive Curve Fit Polynomial Coefficients

Power	N50 [YN(1)]	N60 [YN(2)]	N70 [YN(3)]	N80 [YN(4)]	N90 [YN(5)]	N100 [YN(6)]
0	-37.329	-32.887	-29.637	-25.559	-23.064	-19.946
1	.396089E 2	.326330E 2	.242094E 2	.188936E 2	.173015E 2	.135031E 2
2	.402860E 2	.362146E 2	.371281E 2	.304472E 2	.328997E 2	.311296E 2
3	-.326885E 2	-.256484E 2	-.711639E 1	-.125164E 1	-.559773E 1	-.199635E 1
4	.397695E 1	.348686E 1	-.705366E 1	-.599694E 0	-.167065E 2	-.200747E 2
5	.847350E 1	.747495E 1	-.121721E 2	-.141799E 2	-.505714E 1	-.613206E 1
6	-.188304E 2	-.174840E 2	-.782624E 1	-.133875E 2	.626911E 1	.938014E 1
7	.334908E 0	-.236966E 1	.894936E 1	.915469E 1	.308497E 1	.324620E 1
8	.103131E 2	.102702E 2	.657382E 1	.943453E 1	-.179228E 1	-.279550E 1
9	-.136166E 1	.992354E 0	-.251129E 1	-.251460E 1	-.605389E 0	-.630851E 0
10	-.222623E 1	-.287062E 1	-.224627E 1	-.303990E 1	.301083E 0	.443308E 0
11	.647133E 0	-.217277E 0	.326965E 0	.332880E 0	.410884E-1	.438239E-1
12	.338223E-1	.397733E 0	.366197E 0	.478124E 0	-.206993E-1	-.281713E-1
13	-.132735E 0	.168090E-1	-.164232E-1	-.174528E-1		
14	.553291E-1	-.218380E-1	-.231377E-1	-.294675E-1		
15	.989063E-2					
16	-.574936E-2					

Table C-1  
Interactive Curve Fit Polynomial Coefficients

Power	N110[YN(7)]	N120[YN(8)]	N130[YN(9)]	N140[YN(10)]	N150[YN(11)]
0	-16.682	-13.636	-10.637	-8.880	-6.955
1	.101849E 2	.103644E 2	.800782E 1	.603195E 1	.502563E 1
2	.223191E 2	.191665E 2	.104719E 2	.106262E 2	.784026E 1
3	-.108658E 0	-.867847E 1	-.587329E 1	-.222096E 1	-.261221E 1
4	-.296954E 1	-.102589E 2	.423064E 1	-.348743E 1	-.211257E 1
5	-.587218E 1	.793490E 1	.508267E 1	-.205426E 0	.551911E 0
6	-.100911E 2	-.357415E 1	-.106235E 2	.518022E 0	.292597E 0
7	.333381E 1	-.610692E 1	-.388765E 1	.102580E 0	-.213673E 0
8	.830859E 1	-.697142E 0	.702568E 1	-.198157E-1	-.779550E-1
9	-.891852E 0	.235015E 1	.146642E 1	-.592635E-2	.513869E-1
10	-.281000E 1	.575924E-1	-.225402E 1	-.269964E-2	.209270E-1
11	.124323E 0	-.420471E 0	-.258120E 0		-.396563E-2
12	.443430E 0	-.835171E-3	.354734E 0		-.211007E-2
13	-.718710E-2	.283053E-1	.172570E-1		
14	-.268301E-1		-.218733E-1		

Table C-1  
Interactive Curve Fit Polynomial Coefficients

Curve Fit	Best Fit			Best Fit (Modified)		
	Order	$\sum e^2$	$\bar{e}$	Order	$\sum e^2$	$\bar{e}$
Y50	15	2.1664	0.307	8	70.345	1.749
Y60	15	2.1462	0.305	14	2.1703	0.307
Y70	15	0.41727	0.135	12	1.1915	0.228
Y80	15	0.71421	0.176	18	0.87588	0.195
Y90	15	1.2793	0.236	14	1.2981	0.238
Y100	16	1.1573	0.224	16	1.1573	0.224
Y110	15	1.2798	0.236	13	1.3400	0.241
Y120	15	0.39722	0.131	13	0.77148	0.183
Y130	15	0.54194	0.154	18	0.66737	0.170
Y140	15	0.77259	0.183	16	1.0620	0.215
Y150	15	0.26589	0.108	13	0.44726	0.139
N50	17	0.80547	0.187	16	0.80572	0.187
N60	18	0.63879	0.167	14	0.73449	0.179
N70	17	0.57433	0.158	14	0.59042	0.160
N80	14	0.43632	0.138	14	0.43632	0.138
N90	17	0.77685	0.184	12	0.83329	0.190
N100	15	0.48934	0.146	12	0.67948	0.172
N110	15	0.25701	0.106	14	0.59247	0.160
N120	15	0.29538	0.113	13	0.62067	0.164
N130	15	0.051807	0.047	14	0.064323	0.053
N140	15	0.13166	0.076	10	0.30835	0.116
N150	15	0.11837	0.072	12	0.16549	0.085
Avg.		0.71425	0.176		3.96169	0.252

Table C-2  
Interactive Curve Fit Error Analysis

subroutine FAMIC as YY(1) thru YY(11) and YN(1) thru YN(11). An interpolation algorithm is used to determine the forces and moments at DY points between the curves of each family. Although all the computations are based on measurements from the control ship (ship #2), the interactive forces and moments are also computed for the reference ship (ship #1).

Figures C-1 and C-2 are the interactive forces and moments output to show comparison to figures II-11 and II-12. The speed of this run was the operating point of 15 kts. The ships are of equal length (527.8 feet).

Linear interpolation of the interactive curves for greater than 150 feet DY distance is accomplished from this 150 foot curve to a value of 0.0 at 200 feet. It therefore assumes no force and moment are present outside the 200 foot range. All forces and moments for DY distance of less than 50 feet are taken as that of the 50 foot curve. These two endpoints are by no means exact, but will suffice until more detailed data can be gathered. Another inexact endpoint is produced at the curve families limits of  $\pm 550$  feet. At these points, the forces and moments are forced to 0.0 since detailed data outside of these limits was not available. A side effect of this abrupt truncation will manifest itself in the instantaneous commencement of the forces and moments during the approach phase run. The endpoint variations in some of the curves of figures C-1 and C-2 are due in part to the curve fitting routine used, but mostly to the differences in computer precision. (curve fits were calculated on a 11 digit precision XDS 9300 while the curves were plotted on single precision 7 digit IBM 360/67)

As previously mentioned, the speed modification for other than the operating point of 15 kts. is only completely valid for the situation where both ships are at the same speeds. Since this thesis considered an approach phase

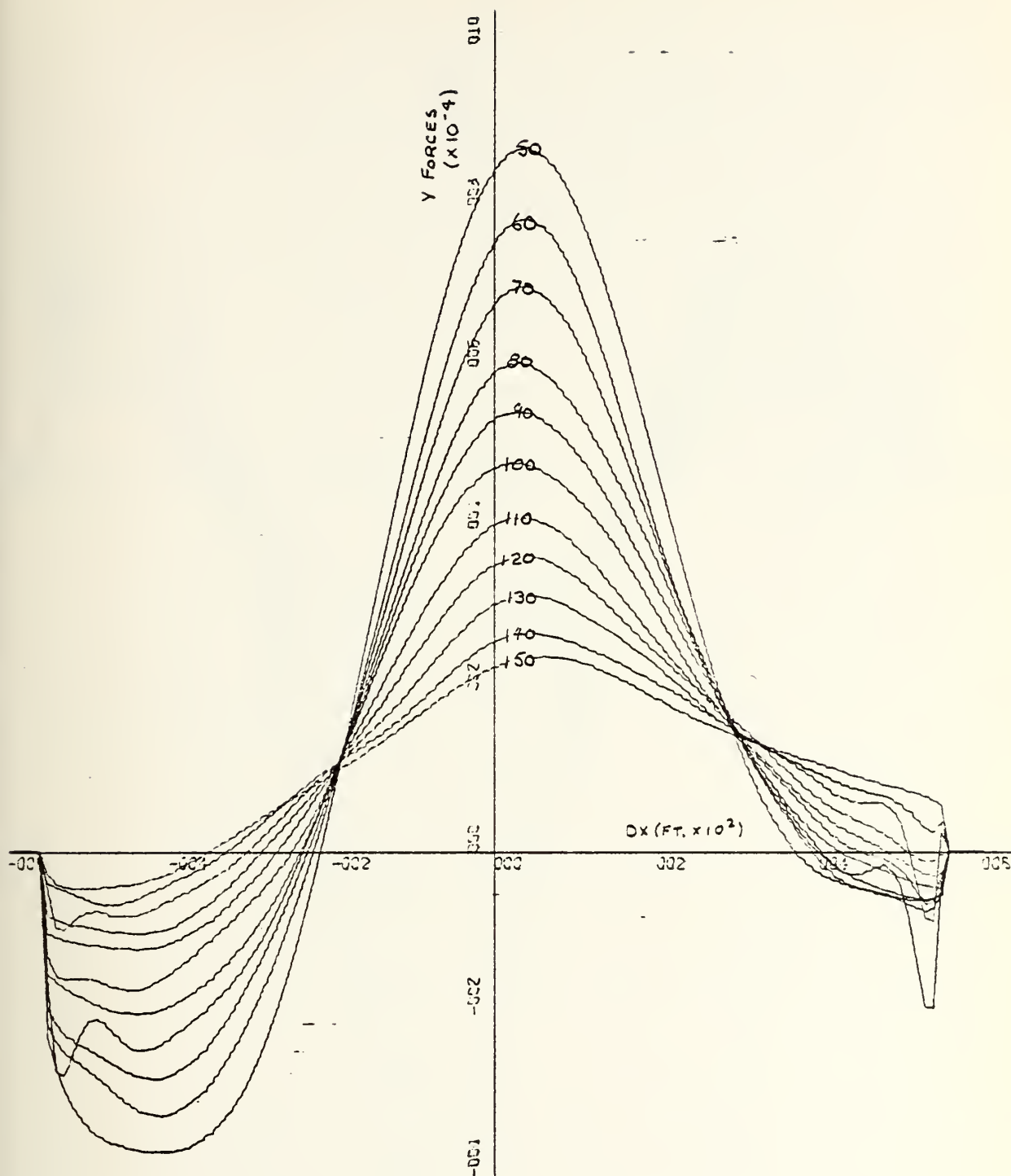


Figure C-1  
Curve Fitted Interactive Y Forces

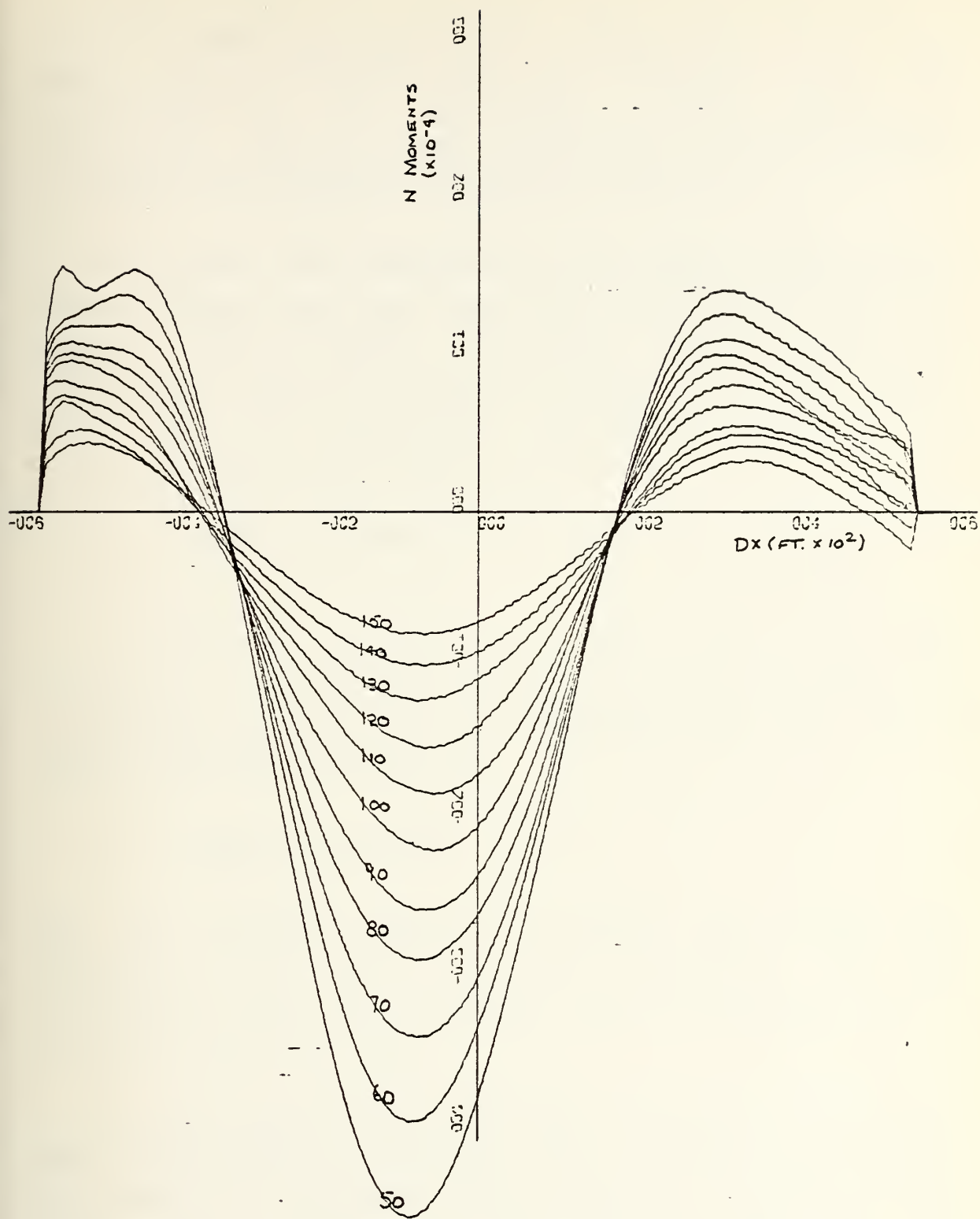


Figure C-2  
Curve Fitted Interactive N Moments

where the control ship enters the interactive field at a speed quite different than the reference ship, some modification of the interactive effects should be considered. However, exact relationships are not available to compute the required modification factors.

To dispel any problems with the design of the heading control system, the worst case speed modification factor was chosen. This factor, in effect, considers that the interactive forces and moments are derived from the control ship. This is accomplished in subroutine FAMIC with the following fortran expression:

$$SFIF2 = C DOT 2^{**2}$$

As stated in chapter II, it is felt that it is more accurate to consider the interactive forces and moments to be modified by the speed of the reference ship, and can be coded in subroutine FAMIC as:

$$SFIF2 = C DOT 1^{**2}$$

With the scenario followed throughout this thesis, this expression would equate to unity throughout the RAS situation, since the reference ship is maintained at 1.0 normalized speed (15 kts.).

For the sake of error analysis, simulation of the worst case modification is performed. This gives rise to forces and moments 2.25 times what they were in the rest of this thesis during a portion of the approach phase when the normalized speed of the control ship is 1.5. Figures C-3 and C-4 show the interactive forces and moments for the approach phase of the simulation. The comparison plots which appear in chapter III as figures III-24 and III-25

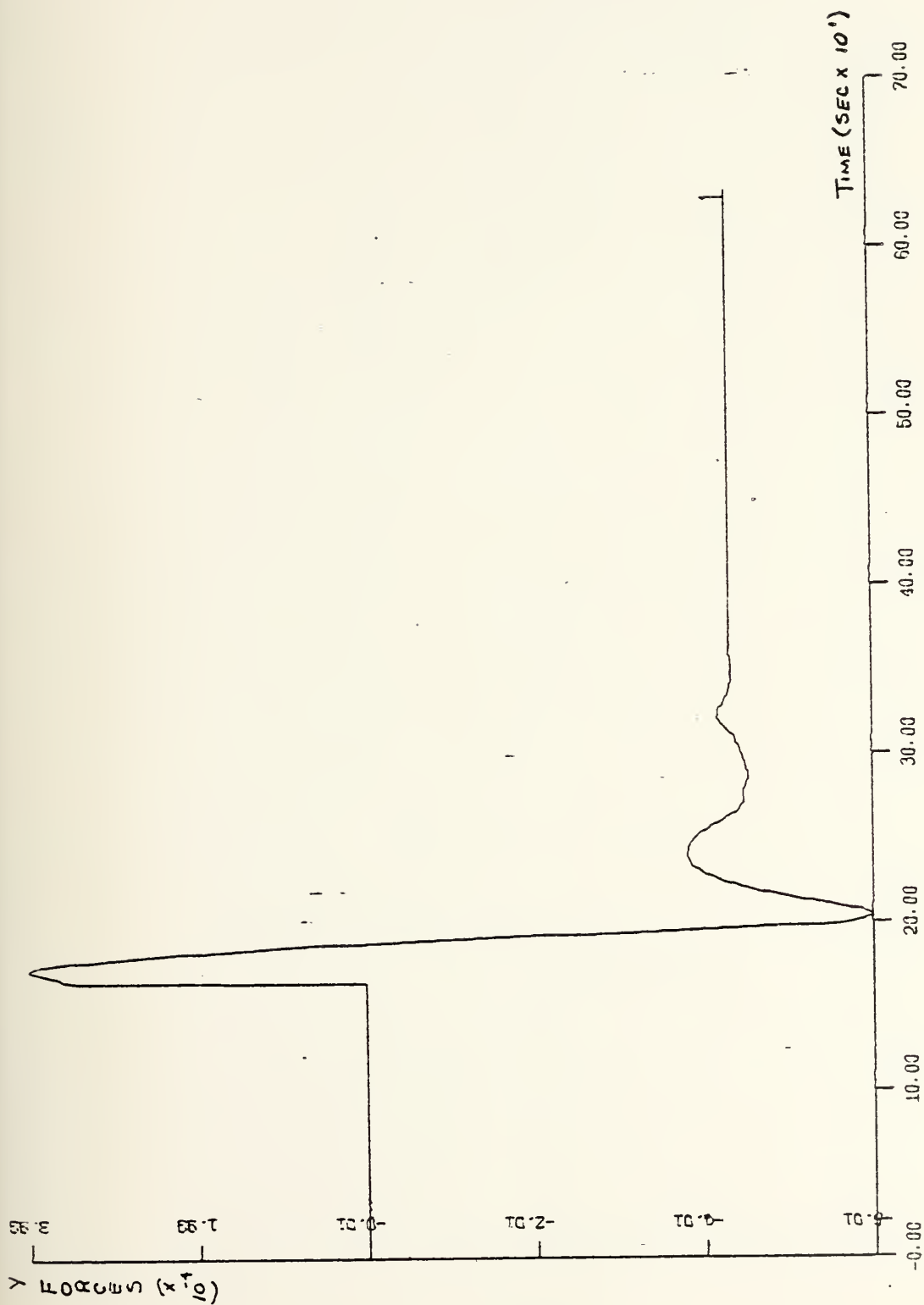


Figure C-3  
Approach Phase Curve Fitted Y Forces

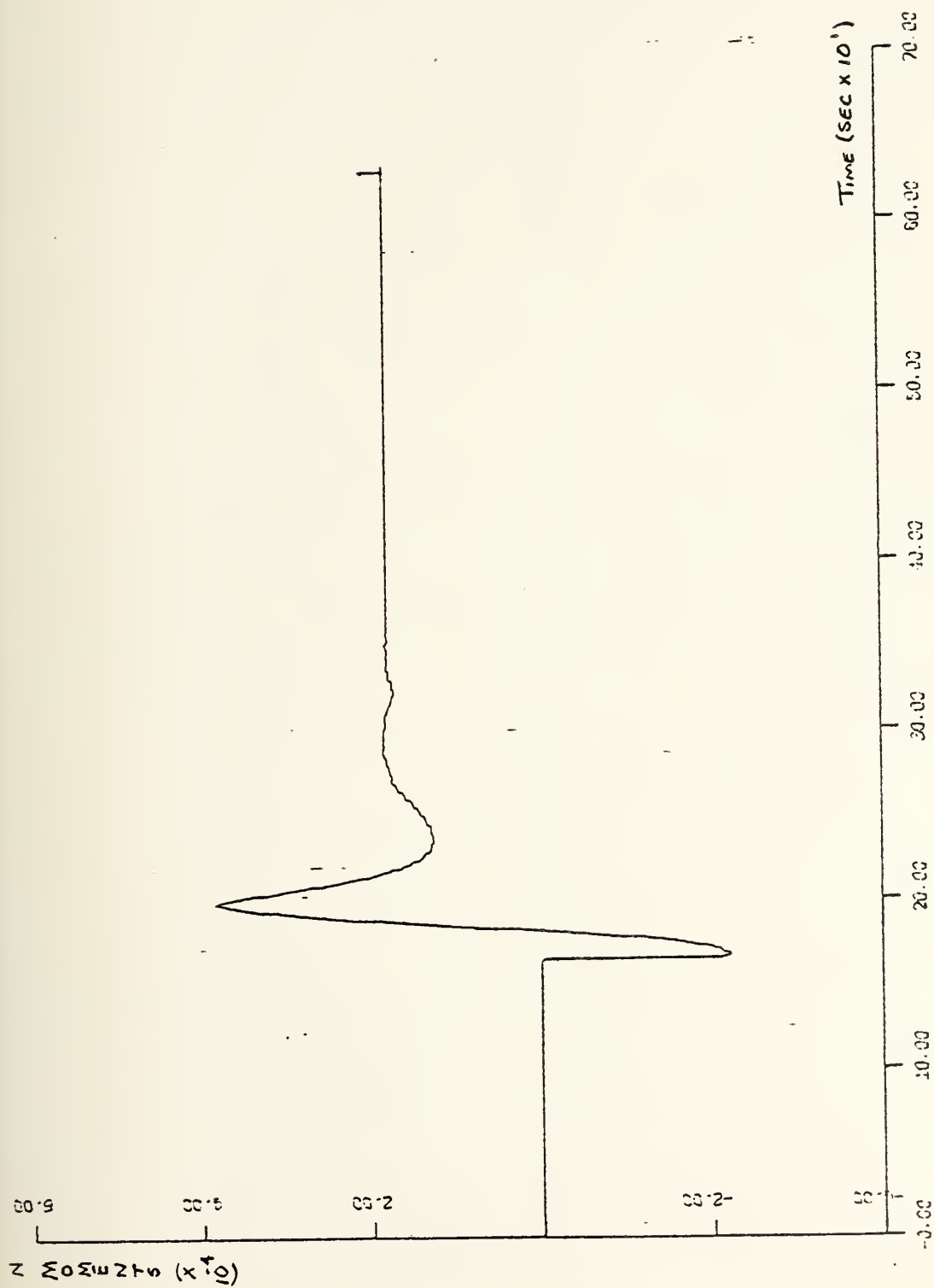


Figure C-4  
Approach Phase Curve Fitted N Moments

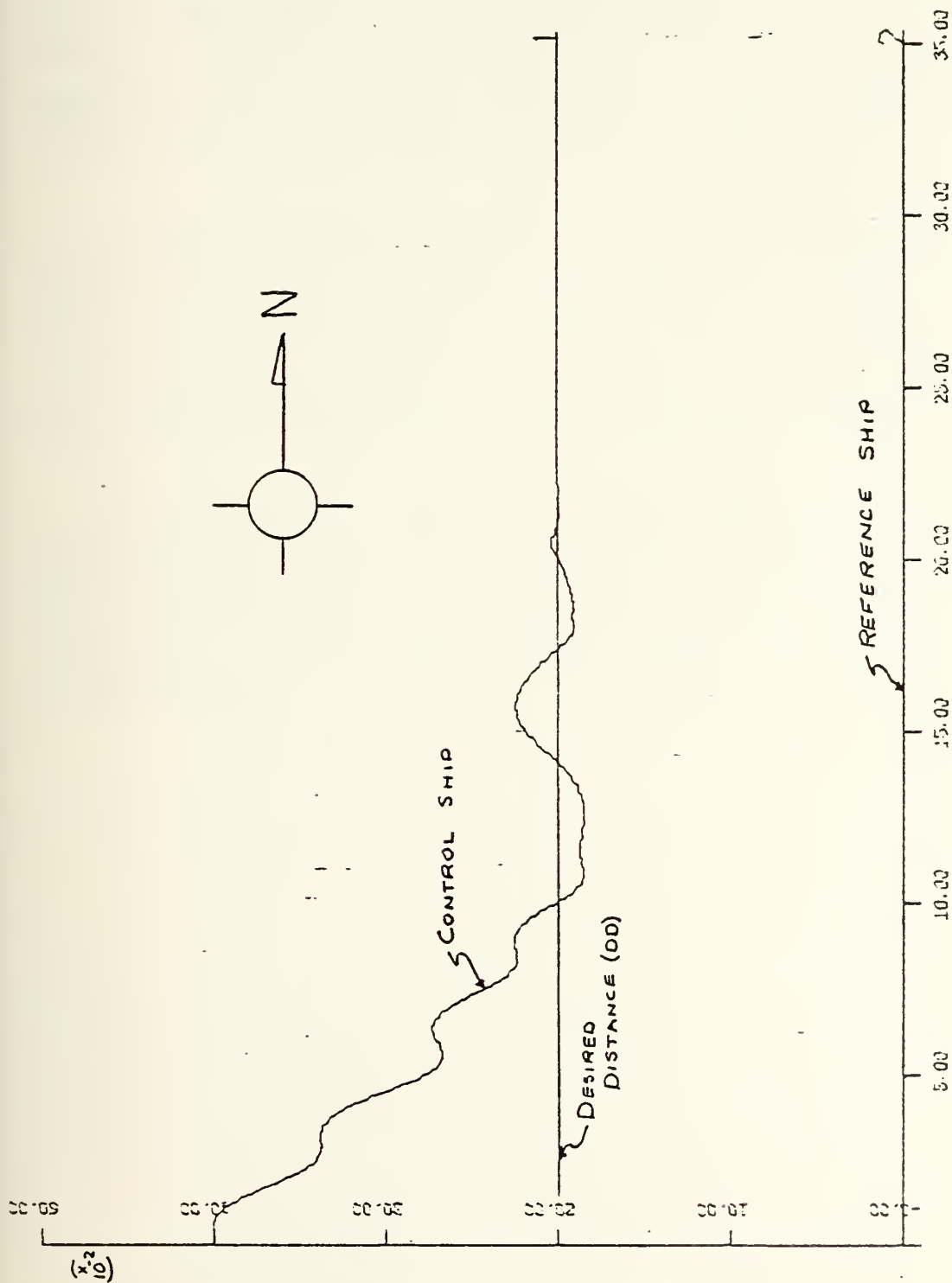


Figure C-5  
Approach Phase Geographical Plot From Modified Interactive Effects

illustrate the extent of the changes. Most notable is the smoother output of subroutine FAMIC. This more realistically portrays the interactive effects in the RAS environment. Figure C-5 portrays the geographical plot which compares with figure III-26 without speed modification. Although differences exist, figure C-5 illustrates that the interactive effects speed modification factor for the worst case does not drastically alter the approach phase outcome. The heading control system design is still valid in the face of these changes.

For reference, figures C-6 and C-7 show the interactive forces and moments in the turn phase as calculated by subroutine FAMIC. Figure C-8 is the turn phase lateral distance plot produced. It can be seen from this illustration that the maximum excursion is 0.0056 normalized distance (2.96 feet), well within acceptable limits.

In summary, the designed control system will accommodate even the worst case modification of the interactive effects. This insensitivity to a large range of perturbations, makes this control system a more viable design for actual ship installation.

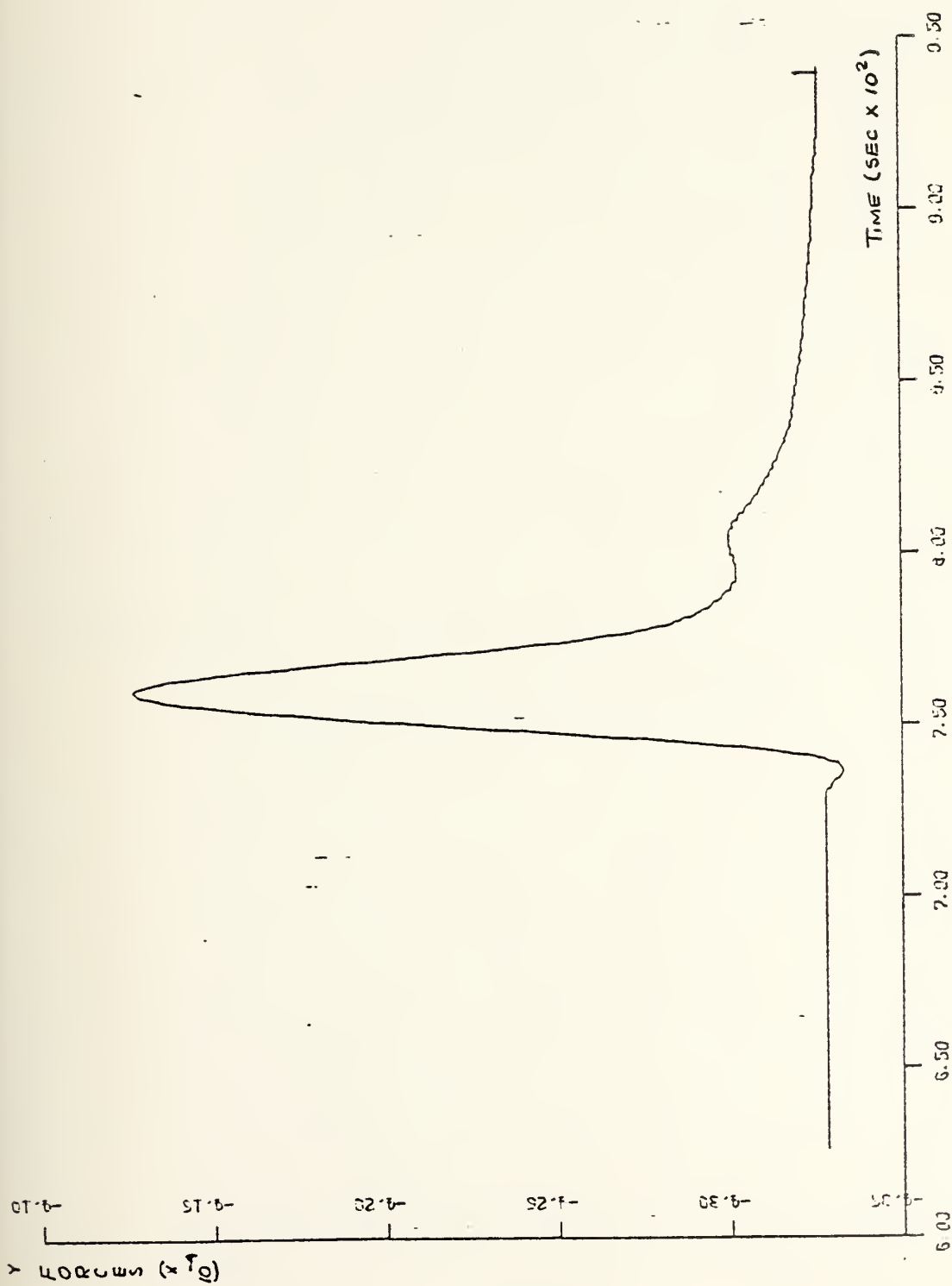
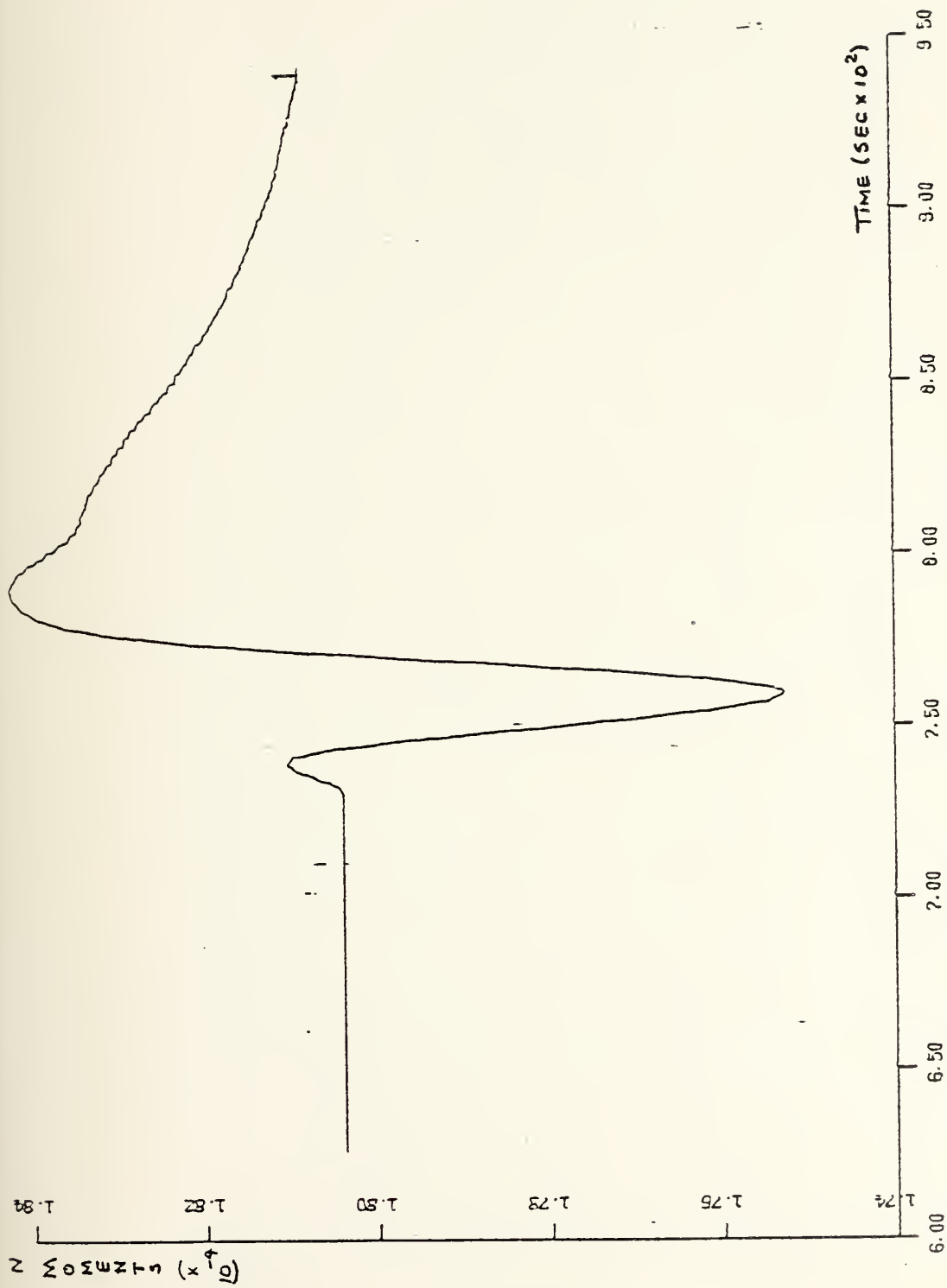


Figure C-6  
Turn Phase Curve Fitted Y Forces



Figure, C-7  
Turn Phase Curve Fitted N Moments

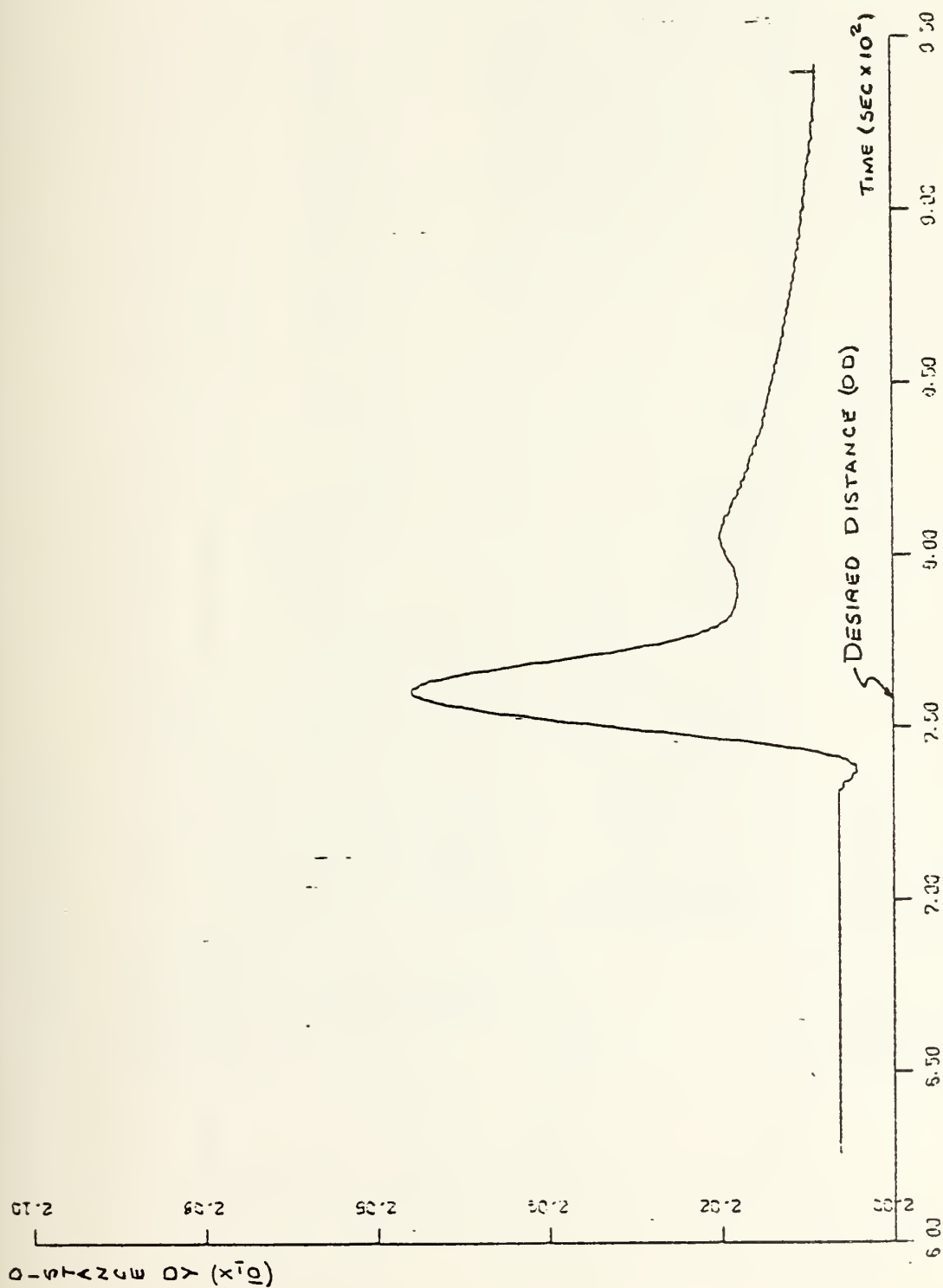


Figure C-8

Turn Phase Lateral Distance  $DY$  From Modified Interactive Effects

# SUBROUTINE FAMIC

SUBROUTINE FAMIC (XL1,XL2,ADX,ADY,CDO11,CDO12,YY1,YY2,YN1,YN2)  
 DIMENSION YY(12), YN(12)

## DEFINITION OF TERMS:

XL1 = LENGTH OF SHIP #1 IN FEET  
 XL2 = LENGTH OF SHIP #2 IN FEET  
 ADX = LONGITUDINAL SEPARATION OF SHIPS (NONDIMENSIONALIZED)  
 ADY = LATERAL SEPARATION OF SHIPS (NONDIMENSIONALIZED)  
 CDO11 = NORMALIZED SPEED OF SHIP #1  
 CDO12 = NORMALIZED SPEED OF SHIP #2  
 YY1 = Y FORCE ON SHIP #1  
 YY2 = Y FORCE ON SHIP #2  
 YN1 = N MOMENT ON SHIP #1  
 YN2 = N MOMENT ON SHIP #2  
 X = LONGITUDINAL SEPARATION NORMALIZED TO CURVE FIT FACTOR

## NOTE:

FOR STBD SIDE TO APPROACH OF SHIP #2 ON SHIP #1, ADY  
 SHOULD BE NEGATIVE.  
 FOR APPROACH WHEN SHIP #2 IS ASTERN OF SHIP #1 ADX SHOULD  
 BE NEGATIVE.  
 CONVERSES ARE ALSO TRUE - PORT SIDE TO = POSITIVE ADY AND  
 FWD OF ALONGSIDE = POSITIVE.  
 ADX AND ADY ARE REFERENCED TO SHIP #2.  
 NORMALIZED SPEEDS BASED ON 15 KTS.

XL = XL2  
 SPDP1 = CDO11\*\*2  
 SPDP2 = CDO12\*\*2  
 XL1 = XL1/XL2  
 XL2 = 1.0  
 N = 1

1 ACXL = XL\*ADX  
 X = XL\*ADX/250.0  
 IF (ABS(ADXL).GT.550.0) GO TO 6

PCLYNOMIAL POWER PRE-COMPUTATION



```

189319E+02*X4+0.875165E+01*X5-0.200712E+02*X6-0.502212E+01*X7+0.615FAMI 920
2353E+01*X8+0.154525E+01*X9-0.972521E+00*X10-0.237633E+00*X11+0.607FAMI 930
2427E-01*X12+0.144010E-01*X13 940
Y(8) = 35.484+0.146142E+02*X1-0.458814E+02*X2-0.158329E+02*X3+0.3FAMI 950
198457E+02*X4+0.163639E+02*X5-0.242537E+02*X6-0.953711E+01*X7+0.820FAMI 960
2245E+01*X8+0.291771E+01*X9-0.137319E+01*X10-0.447954E+00*X11+0.890FAMI 970
38C9E-01*X12+0.272508E-01*X13 980
Y(9) = 30.606+0.138458E+02*X1-0.425663E+02*X2-0.139724E+02*X3+0.6FAMI 990
161640E+02*X4+0.863816E+01*X5-0.800393E+02*X6-0.274913E+01*X7+0.533FAMI 1000
24C7E+02*X8+0.211749E+01*X9-0.175113E+02*X10-0.190223E+01*X11+0.163FAMI 1010
3223E+01*X12+0.777504E+00*X13+0.560018E+00*X14-0.141569E+00*X15-0.1FAMI 1020
460683E+00*X16+0.960782E-02*X17+0.120067E-01*X18 1030
Y(10) = 26.063+0.120761E+02*X1-0.341076E+02*X2-0.150249E+02*X3+0.4FAMI 1040
1574245E+02*X4+0.122510E+02*X5-0.702577E+02*X6-0.333288E+01*X7+0.48FAMI 1050
281C3E+02*X8-0.946233E+00*X9-0.195409E+02*X10+0.766156E+00*X11+0.44FAMI 1060
38663E+01*X12-0.162184E+00*X13-0.548550E+00*X14+0.116108E-01*X15+0.4FAMI 1070
427659E-01*X16 1080
Y(11) = 22.876+0.108418E+02*X1-0.196219E+02*X2-0.127593E+02*X3+0.21FAMI 1090
1133189E+02*X4+0.974262E+01*X5-0.695905E+01*X6-0.335866E+01*X7+0.21FAMI 1100
24837E+01*X8+0.453764E+00*X9-0.339142E+00*X10+0.407256E-03*X11+0.21FAMI 1110
31973E-01*X12-0.347359E-02*X13 1120

```

EQUATIONS OF N MOMENTS

```

YN(1) = -37.329+0.356089E+02*X1+0.402860E+02*X2-0.326885E+02*X3+0.10FAMI 1160
1357655E+01*X4+0.847350E+01*X5-0.188304E+02*X6+0.334508E+00*X7+0.10FAMI 1170
238231E+02*X8-0.136166E+01*X9-0.222623E+01*X10+0.647133E+00*X11+0.33FAMI 1180
4574936E-02*X16 1190
YN(2) = -32.887+0.326330E+02*X1+0.362146E+02*X2-0.256484E+02*X3+0.10FAMI 1200
1348686E+01*X4+0.747495E+01*X5-0.174840E+02*X6-0.236966E+01*X7+0.10FAMI 1210
22702E+02*X8+0.992335E+00*X9-0.287062E+01*X10-0.217277E+00*X11+0.39FAMI 1220
37733E+00*X12+0.168090E-01*X13-0.218380E-01*X14 1230
YN(3) = -29.637+0.242094E+02*X1+0.371281E+02*X2-0.711639E+01*X3-0.65FAMI 1240
1705366E+01*X4-0.121721E+02*X5-0.782624E+01*X6+0.894936E+01*X7+0.36FAMI 1250
27382E+01*X8-0.251129E+01*X9-0.224627E+01*X10+0.326965E+00*X11+0.36FAMI 1260
36197E+00*X12-0.164232E-01*X13-0.231377E-01*X14 1270
YN(4) = -25.559+0.188936E+02*X1+0.304472E+02*X2-0.125164E+01*X3-0.94FAMI 1280
1599694E+00*X4-0.141799E+02*X5-0.133875E+02*X6+0.915469E+01*X7+0.94FAMI 1290
233453E+01*X8-0.251460E+01*X9-0.303990E+01*X10+0.332880E+00*X11+0.47FAMI 1300
38124E+00*X12-0.174528E-01*X13-0.294675E-01*X14 1310
YN(5) = -23.064+0.173015E+02*X1+0.328997E+02*X2-0.559773E+01*X3-0.17FAMI 1320
1167065E+02*X4-0.505714E+01*X5+0.626911E+01*X6+0.308497E+01*X7-0.17FAMI 1330
29228E+01*X8-0.605389E+00*X9+0.301083E+00*X10+0.410884E-01*X11-0.20FAMI 1340
36593E-01*X12 1350
YN(6) = -19.946+0.135031E+02*X1+0.311296E+02*X2-0.195635E+01*X3-0.27FAMI 1360
1200747E+02*X4-0.613206E+01*X5+0.938014E+01*X6+0.324620E+01*X7-0.27FAMI 1370
29550E+01*X8-0.630851E+00*X9+0.443308E+00*X10+0.438239E-01*X11-0.28FAMI 1380

```

```

31713E-01*X12      101849E+02*X1+0.223191E+02*X2-0.108658E+00*X3-0.      FAMI11400
  YN(7) = -16.682+0.587218E+00*X5-0.100911E+02*X6+0.333381E+01*X7+0.83      FAMI11410
1256954E+01*X8-0.891852E+00*X9-0.281000E+01*X10+0.124323E+00*X11+0.44      FAMI11420
206559E+01*X12-0.718710E-02*X13-0.268301E-01*X14      FAMI11430
334330E+00*X12-0.13.636+0.103644E+02*X1+0.191665E+02*X2-0.867847E+01*X3-0.      FAMI11440
  YN(8) = -13.636+0.103644E+02*X1+0.191665E+02*X2-0.867847E+01*X3-0.      FAMI11450
117142589E+02*X4+0.793490E+01*X5+0.357415E+01*X6-0.610652E+01*X7-0.69      FAMI11460
271242E+00*X8+0.235015E+01*X9+0.575924E-01*X10-0.420471E+00*X11-0.83      FAMI11470
35171E-03*X12+0.283053E-01*X13      FAMI11480
  YN(9) = -10.637+0.800782E+01*X1+0.104719E+02*X2-0.587329E+01*X3+0.      FAMI11490
1423064E+01*X4+0.508267E+01*X5-0.106235E+02*X6-0.388765E+01*X7+0.70      FAMI11500
22568E+01*X8+0.146642E+01*X9-0.225402E+01*X10-0.258120E+00*X11+0.35      FAMI11510
34734E+00*X12+0.172570E-01*X13-0.218733E-01*X14      FAMI11520
  YN(10) = -8.880+0.603195E+01*X1+0.106262E+02*X2-0.222096E+01*X3-0.      FAMI11530
1348743E+01*X4-0.205426E+00*X5+0.518022E+00*X6+0.102580E+00*X7-0.19      FAMI11540
281157E-01*X8-0.955+0.502563E-02*X9-0.269964E-02*X10      FAMI11550
  YN(11) = -6.955+0.502563E-02*X9-0.269964E-02*X10      FAMI11560
1211257E+01*X4+0.551911E+00*X5+0.784026E+01*X6-0.213673E+00*X7-0.77      FAMI11570
29550E-01*X8+0.513869E-01*X9+0.209270E-01*X10-0.396563E-02*X11-0.21      FAMI11580
31007E-02*X12      FAMI11590
  ACYA = ABS(ADY)      FAMI11600
  ADYL = XL2*ADYA      FAMI11610
  XII = (ADYL-40.0)/10.0      FAMI11620
  I = XII      FAMI11630
  IF (XII.LT.1.0.OR.I.LT.1) GO TO 4      FAMI11640
  IF (XII.GT.11.0.OR.I.GT.11) GO TO 5      FAMI11650
  IF (XII.LT.XII) GO TO 2      FAMI11660
  IF (XII.GT.XII) GO TO 3      FAMI11670
  YVI = YN(I)      FAMI11680
  YNI = YN(I)      FAMI11690
  GC TO 7      FAMI11700
  YVI = YN(I)+(YV(I+1)-YV(I))*((XII-XI))      FAMI11710
  YNI = YN(I)+(YV(I+1)-YV(I))*((XII-XI))      FAMI11720
  GC TO 7      FAMI11730
  YVI = YN(I)-(YV(I)-YV(I-1))*((XII-XI))      FAMI11740
  YNI = YN(I)-(YV(I)-YV(I-1))*((XII-XI))      FAMI11750
  GC TO 7      FAMI11760
  YVI = YN(I)      FAMI11770
  YNI = YN(I)      FAMI11780
  GC TO 7      FAMI11790
  YVI = YN(I)      FAMI11800
  YNI = YN(I)      FAMI11810
  IF (ADYL.GT.200.0) GO TO 6      FAMI11820
  YVI = YN(11)*(1.0+(150.0-ADYL)/50.0)      FAMI11830
  YNI = YN(11)*(1.0+(150.0-ADYL)/50.0)      FAMI11840
  GC TO 7      FAMI11850
  YVI = 0.0      FAMI11860
  YNI = 0.0      FAMI11870

```

C

```

YN1 = 0.0
YN2 = 0.0
RETURN
7 IF (N*EC.2) GO TO 8
  YY1*SPDP2*XL P2*1.0E-05
  YN2 = -YN1*SPDP2*XL P2*1.0E-05
  N = N+1
  XL = -XL2
  GO TO 1
8 YY1 = YY1*SPDP1*XL P1*1.0E-05
  YN1 = YN1*SPDP1*XL P1*1.0E-05
  IF (ADY.LT.0.0) GO TO 9
  RETURN
9 YY1 = -YY1
  YY2 = -YY2
  YN1 = -YN1
  YN2 = -YN2
  RETURN
END

```

```

FAMI11880
FAMI11890
FAMI11900
FAMI11910
FAMI11920
FAMI11930
FAMI11940
FAMI11950
FAMI11960
FAMI11970
FAMI11980
FAMI11990
FAMI12000
FAMI12010
FAMI12020
FAMI12030
FAMI12040
FAMI12050
FAMI12060

```

## COMPUTER PROGRAM #1

This program incorporates the ship dynamics of two identical Mariner hulls. These hulls are superimposed in space to allow for comparison of the effects contributed to rudder modeling differences. In this particular run a step and ramp rudder were compared in chapter II.

Another benefit of this program is to set up the two identical ships required for the RAS simulations in chapter III. Basically, verification of the models in three degrees of freedom is accomplished for the Mariner hull chosen.

The plots produced in this run are shown in figures II-2 and II-3.

# COMPUTER PROGRAM #1

```

//UHRINTF1 JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=2
// EXEC DSL
//DSL.INPUT DD *
* LINEAR RESPONSE OF THE MARINER - RAMP VS STEP RUDDER COMPARISON
* LINEAR RESPONSE OF THE MARINER - RAMP VS STEP RUDDER COMPARISON
TITLE TRAPZ
INTEGER NPLOT=1
CONST NPLOT=1
* HYDRODYNAMIC COEFFICIENTS
CONST NR=-0.00227,NV=-0.00351,NVD=-0.000197
CONST MYVD=0.015,MYR=0.0051,I2NRD=0.00068,MXUD=0.0085
CONST YV=-0.01243,XJ=-0.0012,YRD=-0.00027
CONST YDEL=-0.0027,NDEL=-0.00126,XDEL=-0.0
* INITIAL CONDITIONS
INCON X01=0.0,Y01=0.0,X02=0.0,Y02=0.0
INITIAL
* CALCULATION OF THE COEFFICIENTS
D1=0.0
D2=0.0
NC1=-XU
NC2=-XU
A11=MYVD
B11=-YV
A21=-YRD
B21=MYR
A12=-NV
B12=-NV
A22=I2NRD
B22=-NR
A33=MXUD
B33=-XU
KAI=-YDEL
KB1=NDEL
KC1=XDEL
D=A11*A22-A12*A21
DELRM=41.6953
RDC=180./3.1415926
DRC=3.1415926/180.
LUC=20.84765
DERIVATIVE
* SIMULATION SHIP A
IF1=KAI*D1
IF21=KB1*D1

```

```

IF31=KC1*DI+NC1
I11=-B11*ADOT1-B21*BDO11+IF11
I21=-B12*ADOT1-B22*BDO11+IF21
I31=-B33*CDOT1+IF31
ADDOT1=(I11*A22-I21*A21)/D
BDDOT1=(I21*A11-I11*A12)/D
CDDOT1=I31/A33
ADOT1=INTGRL(0.,ADDOT1)
BDO11=INTGRL(0.,BDDOT1)
CDO11=INTGRL(1.0,CDDOT1)
B1=INTGRL(0.,BDO11)
XDOT1=CDO11*COS(B1)-ADOT1*SIN(B1)
YDOT1=CDO11*SIN(B1)+ADOT1*COS(B1)
X1=INTGRL(X01,XDOT1)
Y1=INTGRL(Y01,YDOT1)
YAW1=B1
SWAY1=Y1
SURGE1=X1
SIMULATION SHIP B
IF12=KB1*D2
IF22=KB1*D2
IF32=KC1*D2+NC2
I12=-B11*ADOT2-B21*BDO12+IF12
I22=-B12*ADOT2-B22*BDO12+IF22
I32=-B33*CDOT2+IF32
ADDOT2=(I12*A22-I22*A21)/D
BDDOT2=(I22*A11-I12*A12)/D
CDDOT2=I32/A33
ADOT2=INTGRL(0.,ADDOT2)
BDO12=INTGRL(0.,BDDOT2)
CDO12=INTGRL(1.0,CDDOT2)
B2=INTGRL(0.,BDO12)
XDOT2=CDO12*COS(B2)-ADOT2*SIN(B2)
YDOT2=CDO12*SIN(B2)+ADOT2*COS(B2)
X2=INTGRL(X02,XDOT2)
Y2=INTGRL(Y02,YDOT2)
YAW2=B2
SWAY2=Y2
SURGE2=X2
DYNAMIC REGION
RUDDER RESPONSE INPUT
D1=0.2618*STEP(2.0)
D2=RAMP(2.0)*DELRM*DRC
IF(D2*GE.0.2618) D2=0.2618
SWAYD=SWAY2-SWAY1
SURGED=SURGE2-SURGE1
YAWD1=YAW1*RDC
YAWD2=YAW2*RDC

```

\*

\*

```

YAWDD=YAWD1-YAWD2
D1D=D1*RDC
D2D=D2*RDC
DDD=D1D-D2D
ATIME=LUC*TIME

SAMPLE 0.04, ATIME, YAWD1, D1D, YAWD2, D2D, YAWDD, DDD
PRINT
CONTRL FINIM=30., DELT=0.04, DELS=0.04
PRPLOT ONLY
CALL DRWG(1,1, SURGE1, SWAY1)
CALL DRWG(1,2, SURGE2, SWAY2)
CALL DRWG(2,1, ATIME, YAWDD)
CALL DRWG(3,1, ATIME, DDD)

TERMINAL
CALL ENDRW(NPLOT)

END
STOP
//PLOT.SYSIN DD *

```

0.0	1.0	-5.0	1.0	8.0	6.0	5
0.0	100.0	-6.0	1.0	8.0	6.0	5
INSERT TWO /* CARDS HERE						4
				7.0	5.0	

## COMPUTER PROGRAM #2

This program models a practical rudder response for a mariner ship type. The rudder limits (stops) are set at  $\pm 30$  degrees and the rate of response is limited to  $\pm 2$  degrees/sec. A scale factor (LUC) is introduced to modify the response to match real time of the mariner hull chosen.

Twelve passes thru the program are accomplished to conform to different sets of initial conditions and final desired rudder conditions. The plots produced in this run are shown in figures II-5 and II-6.

COMPUTER PROGRAM #2

```
//UHRINTF2 JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=1
//EXEC DSL
//DSL INPUT DD *
* RAS RUDDER CONTROL RUN TF2 - PRACTICAL RUDDER RESPONSE
* TITLE RAS RUDDER CONTROL RUN TF2 - PRACTICAL RUDDER RESPONSE
INTEG TRAPZ
INTEGER NPLOT,CURVE
CONST NPLOT=2
CONST DLTDM=2.0,DLTEM=7.0
PARAM CURVE=1
PARAM D2DDES=30.0
PARAM D2DIC=-30.0
INITIAL
  KG=DLTDM/DLTEM
  LUC=20.84765
DERIVATIVE
  DLTS=LIMIT(-30.0,30.0,D2DDES)
  DLTE=DLTS-D2D
  DLTE=LIMIT(-DLTEM,DLTEM,DLTE)
  D2D=INTGRL(D2DIC,KG*DLTE*LUC)
  ACTUAL TIME CONVERSION
  ATIME=TIME*LUC
*
SAMPLE FINTIM=1.7,DELT=0.04,DELS=0.04
CONTRL PRINT 0.04,ATIME,DLTS,DLTE,DLTE,D2D,D2DDES,D2DIC
PRPLOT ONLY
CALL DRWG(1,CURVE,ATIME,D2D)
TERMINAL
WRITE(6,100)D2DIC,D2DDES
100 FORMAT(//,' LAST RUN IS FOR INITIAL RUDDER=',F10.5,' DESIRED RUDDER=
1 R=,F10.5)
D2DDES=D2DDES-5.0
D2DIC=D2DIC+5.0
CURVE=CURVE+1
IF(NPLOT.EQ.1) D2DIC=0.0
IF(CURVE.EQ.7) GO TO 1
GO TO 2
1 CURVE=1
D2DIC=0.0
D2DDES=30.0
CALL ENDRW(NPLOT)
2 CALL RERUN
END
```

END  
STOP  
//PLOT.SYSIN DD \*

0.0      5.0      -30.0      10.0      7.0      6.0

5

0.0  
INSERT TWO /\* CARDS HERE

0.0

7.0

5.0

5

### COMPUTER PROGRAM #3

This program models a reduced order (first order) gas turbine propulsion plant for an input-output relationship. The program does not scale the plant to the mariner hull used. This was done when introduced into the main simulation program first listed as computer program #8.

The time delay (P) is assisted in initialization by a dual feed into the system; one thru the delay itself and one directly into SPDIN. The program can be modified to compare a family of curves by introducing the following sequence into the TERMINAL region:

```
INTEGER NUMB
```

```
IF (NCUR.EQ.NUMB) CALL ENDEW(NPLOT)
```

```
IF (NCUR.NE.NUMB) CALL RERUN
```

```
NCUR = NCUR + 1
```

where NUMB is the number of curves desired (less than or equal to 10) which is set with a PARAM statement. The comparison is done on the conditions set in the terminal region [i.e. decrement or increment the system gains (eg.  $G = G + 0.02$ )].

The plot produced by this run is shown as part of figure II-10.

# COMPUTER PROGRAM #3

```

//UHRINTF3 JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=2
// EXEC DSL
//DSL.INPUT DD *
TITLE SPEED CONTROL - FIRST ORDER FIT
INTEG RKSFY
INCON UIC=20.0
INTEGER NPLOT,NCUR
PARAM NPLOT=1
PARAM UF=21.73
PARAM A=22.0
PARAM P=0.0
PARAM NCUR=1
PARAM G=0.092
INITIAL
K=UF/A
WRITE(6,100) G,NCUR,K
100 FORMAT(//,1 THE FOLLOWING RUN FOR POLE=--,F10.5/,23X,'NCUR=',
113,/,23X,'K=',F10.5,/)
DERIVATIVE
SPDDES=20.25
SPDDES=1.75*STEP(10.0)
SPDDEL=DELAY(7,P,SPDDES)
SPDIN=K*SPDDEL+K*SPDDES
SPDEKR=(SPDIN-SPDOUT)*G
SPDOUT=INTGRL(UIC,SPDERR)
DYNAMIC
IF (TIME.GT.9.0) P=4.88
SAMPLE
CONTROL FINTIM=320.0,DELT=0.8,DELS=0.8
PRINT 1.6,SPDDES,SPDDEL,SPDIN,SPDERR,SPDOUT,P
TERMINAL
CALL ENDRW(NPLOT)
END
STOP
//PLCT.SYSIN DD *
0.0 40.0 20.0 0.4 8.0 5.0
INSERT TWO /* CARDS HERE

```

#### COMPUTER PROGRAM #4

This program models a simplified wave simulation composed of two superimposed sinusoids (fundamental and second harmonic) and a small random wave. The model is inherently scaled to the mariner nondimensional characteristics. Introduction of these waves is accomplished in computer program #7. Subroutine DEGRAD is shown in appendix A.

The sea state force plots in the dimensions of the three degrees of freedom produced by this run is shown in figures II-17 thru II-22.

# COMPUTER PROGRAM #4

```

//UHRINTF4 JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=2
// EXEC DSL
//DSL.INPUT DD *
* TITLE WAVE PERTURBATION SIMULATION
  INTGER NPLOT
  PARAM NPLOT=6
  PARAM YAWDP2=0.0
  PARAM CDOT2=1.5
  PARAM LUC=20.84765
  PARAM WS=5.0
  PARAM WD=015.0
  PARAM WL=0.5
  PARAM WFMA=0.1137
  ATIME=LUC*TIME
  WFI=(WFMA/(0.1137*40.0))*RAMP(0.0)
  WF=LIMIT(-WFMA,WFMA,WFI)
  WRV=NORMAL(1975,0.0,WFMA/10.0)
  WV=WS/15.0
  EWDD=WD-YAWDP2
  EWD=DEGRAD(1,1,EWDD)
  WEF=2.0*3.1415926*(CDOT2+WV*COS(EWD))/WL
  WE=WEF*TIME
  WFY=WF*SIN(EWD)
  WFN=WF*SIN(2.0*EWD)
  WFX=WF*WV*SIN(EWD)
  WYF=WF*WV*SIN(WE)
  WNF=WF*WV*SIN(WE)+(3.1415926*WV**2/WL)*SIN(2.0*WE)
  WXF=WF*WV*SIN(WE)+(3.1415926*WV**2/WL)*SIN(2.0*WE)
  WY=WF*WV*WV*WV*SIN(WE)
  WN=WNF+WRV*WV*WV*SIN(WE)
  WX=WXF+WRV*WV*WV*SIN(WE)
  WED=DEGRAD(0,1,WE)

SAMPLE 0.04,ATIME,WY,WYF,WN,WNF,WX,WXF,WED,WRV
PRINT ONLY
PRPLOT FINT IM=5.0,DELT=0.04,DELS=0.04
CONTROL CALL DRWG(1,1,ATIME,WX)
        CALL DRWG(1,2,ATIME,WY)
        CALL DRWG(1,3,ATIME,WN)
TERMINAL
WRITE(6,100) WS,WD,WL,WFMA,CDOT2
100 FORMAT(//,' LAST RUN FOR WS=',F10.5,/,14X,'WD=',F10.5,/,14X,'WL=',

```

```

1 F10.5/,14X,'WFMA=',F10.5/,14X,'C DOT2=',F10.5,///)
  CALL ENDRW(NPLOT)
END
PARAM WL=1.0
END
PARAM WL=1.5
END
PARAM WD=030.0
PARAM WL=0.5
END
PARAM WL=1.0
END
PARAM WL=1.5
END
STOP
FORTRAN
INSERT FUNCTION DEGRAD FROM APPENDIX A HERE
//PLOT.SYSIN DD *

```

7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4

INSERT TWO /\* CARDS HERE

## COMPUTER PROGRAM #5

This program uses the mariner hull model first introduced in computer program #1 and the control system designed in chapter III to simulate the approach phase of RAS. The subroutines and functions that are to be inserted from appendix A can also be done in object code by changing the word FORTRAN to OBJECT and placing pre-compiled decks in the same locations. In fact, due to the long length of subroutine SLOPES, this must be done to be able to run the simulation with the DSL default job control language (JCL) presently installed at the Naval Postgraduate School IBM 360/67.

The plots produced by this run are shown in figures III-7 thru III-13. By changing the gains and introducing the following code, the plots of figures III-14 thru III-19 are produced:

$$DIDES = 5.0*STEP(8.0) - 5.0*STEP(9.0)$$

# COMPUTER PROGRAM #5

```
//UHRINTF5 JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=4
// EXEC DSL
//DSL.INPUT DD *
* TITLE RAS RUDDER CONTROL - APPROACH PHASE
* INTEG RKSFY
* INTEG NPLT=1
* INTEG N,IS
* CONST N=1,RD=1.0
* CONST IS=1,DD=0.2
* PARAM RSENS=1.86642,WTSENS=2.3869,RGN=23.4185,VFBG=4.35162
* CONST NR=-0.00227,NV=-0.00351,NVD=-0.000197
* CONST MYVD=0.015,MYR=0.0051,IZNRD=0.00068,MXUD=0.0085
* CONST YV=-0.01243,XU=-0.0012,YRD=-0.00027
* CONST YDEL=-0.0027,NDEL=-0.00126,XDEL=-0.0
* CONST DLDM=2.0,DLTEM=7.0
* INITIAL SEPERATION
* INCON X01=5.0,Y01=0.0,X02=0.0,Y02=0.4
* INCON YAW01=0.0
* INCON Y01=0.,YY2=0.,YN1=0.,YN2=0.
* INCON U01=1.0,U02=1.5
INITIAL
DY0=Y02-Y01
DX0=X02-X01
CALL TRANS(YAW01,DX0,DY0,ADX,ADY)
CALL SLOPES(ADX,ADY,YY1,YY2,YN1,YN2)
CALCULATION OF THE COEFFICIENTS
NC1=-XU
NC2=-XU
A11=MYVD
B11=-YV
A21=-YRD
B21=MYR
A12=-NVD
B12=-NV
A22=IZNFD
B22=-NR
A33=MXUD
B33=-XU
```

```

KAI=-YDELR
KBI=NDELR
KCI=XDELR
D=A11*A22-A12*A21
DELRM=41.6953
RDC=180./3.1415926
CRC=3.1415926/180.
LUC=20.84765
KG=DLTDM/DLTEM
D2D=0.0

DERIVATIVE
*
REFERENCE SHIP RUDDER CONTROL
DIDES=0.0
DLTSI=LIMIT(-30.0,30.0,DIDES)
DLTEI=DLTSI-DID
DLTBEI=LIMIT(-DLTEM,DLTEM,DLTEI)
DID=INTGRL(DIDIC,KG*DLTBEI*LUC)
DI=DEGRAD(1,1,DID)
DX=X2-X1
DY=Y2-Y1
SIMULATION SHIP A
*
IF11=KAI*D1
IF21=KBI*D1
IF31=KCI*D1+NC1
I11=-B11*ADOT1-B21*BDOOT1+IF11
I21=-B12*ADOT1-B22*BDOOT1+IF21
I31=-B33*CDOT1+IF31
ADDOT1=(I11*A22-I21*A21)/D
BCDOT1=(I21*A11-I11*A12)/D
CDDOT1=I31/A33
ADOT1=INTGRL(0.,ADDOT1)
BCOT1=INTGRL(0.,BCDOT1)
CDOCT1=INTGRL(U01,CDDOT1)
BY1=INTGRL(0.,BDOOT1)
XDOT1=CDOT1*COS(BY1)-ADOT1*SIN(BY1)
YDOT1=CDOT1*SIN(BY1)+ADOT1*COS(BY1)
X1=INTGRL(X01,XDOT1)
Y1=INTGRL(Y01,YDOT1)
YAW1=BY1
SWAY1=Y1
SURGE1=X1
SIMULATION SHIP B
*
IF12=KAI*D2+YY2
IF22=KBI*D2+YN2
IF32=KCI*D2+YC2
I12=-B11*ADOT2-B21*BDOOT2+IF12
I22=-B12*ADOT2-B22*BDOOT2+IF22
I32=-B33*CDOT2+IF32

```

```

ADDOT2=(I12*A22-I22*A21)/D
BDDOT2=(I22*A11-I12*A12)/D
CDDOT2=I32/A33
ADOT2=INTGRL(0.,ADDOT2)
BCOT2=INTGRL(0.,BDDOT2)
COT2=SPDCTR(ADX,U01,U02)
BY2=INTGRL(BY02,BDOT2)
XDOT2=CDDOT2*COS(BY2)-ADDOT2*SIN(BY2)
YDOT2=CDDOT2*SIN(BY2)+ADDOT2*COS(BY2)
X2=INTGRL(X02,XDOT2)
Y2=INTGRL(Y02,YDOT2)
YAW2=BY2
SWAY2=Y2
SURGE2=X2

NOSORT
YAWD1=DEGRAD(0,0,YAW1)
YAWDP1=DEGRAD(0,1,YAW1)
YAWD2=DEGRAD(0,0,YAW2)
YAWDP2=DEGRAD(0,1,YAW2)
RUDDER RESPONSE INPUT
CALL RBMEAS(N,YAW1,X1,Y1,YAW2,X2,Y2,RD,R1,B1,BB1,R2,B2,BB2)
CALL HDGRAS(N,IS,R1,B1,BB1,R2,B2,BB2,RSENS,YAW2,PSIDFD,PSIADD,...)
PSIDED,WT,DA,AID,BID,B2D,WTSENS,DD,RD)
BCOT2D=DEGRAD(0,1,BDOT2)
BDOTFB=VFBG*BDOT2D
DDUMB=YAWD2-PSIDED+BDOTFB
IF(DDUMB.GT.180.0) DDUMB=DDUMB-360.0
IF(DDUMB.LT.-180.0) DDUMB=360.0+DDUMB
DLTS=LIMIT(-30.0,30.0,DDUMB*RGD)
DLTE=DLTS-D2D
DLTBE=LIMIT(-DLTEM,DLTEM,DLTE)
D2D=INTGRL(D2DIC,KG*DLTBE*LUC)
D2=DEGRAD(1,1,D2D)

SORT
RUDDER PART OF OBJECT FUNCTION
DTRAN=TIME*ABS(D2)
ROBJ=INTGRL(0.0,DTRAN)
DISTANCE PART OF OBJECT FUNCTION
DISTE=TIME*10.0*ABS(DD-ADY)
DCBJ=INTGRL(0.0,DISTE)
OBJECT FUNCTION
OBJ=ROBJ+DOBJ
ACTUAL SEPARATION
DX=X2-X1
DY=Y2-Y1
CALL TRANS(YAW1,DX,DY,ADX,ADY)
EXTERNAL FORCES ACTING BETWEEN SHIPS

```

```

CALL SLOPES(ADX,ADY,YY1,YY2,YN1,YN2)
IF((ABS(ADY).LT.0.04744).AND.(ABS(ADX).LT.1.0)) WRITE(6,100)
FORMAT(1, '*****SEPARATION LESS THAN 25 FEET - COLLISION*****')
100 ACTUAL TIME CONVERSION (SEC)
* ATIME=LUC*TIME

SAMPLE FINT IM=20., DELT=0.04, DELS=0.04
CONTFL 0.04,X1,X2,DA,AID,PSIDFD,Y1,Y2,R1,BID,PSIADD,YAWD1,YAWD2,R2,...
PRINT B2D,PSIDED,ATIME,D2D,ADX,DID,YY2,BDOTFB,DLTS,ADY,DLTS1,...

PRPLOT YN2,CDO1,CDOT2,OBJ
CNLY
CALL DRWG(1,1,ATIME,YAWDP2)
CALL DRWG(1,2,ATIME,YAWDP1)
CALL DRWG(2,1,ATIME,YY2)
CALL DRWG(3,1,ATIME,YN2)
CALL DRWG(4,1,SURGE2,SWAY2)
CALL DRWG(4,2,SURGE1,SWAY1)
CALL DRWG(5,1,ATIME,ADY)
CALL DRWG(6,1,ATIME,DLTS)
CALL DRWG(6,2,ATIME,D2D)

TERMINAL
IF(IS.EQ.1) WRITE(6,101)
101 FORMAT(1, 'THIS RUN IS FOR A PORT SIDE TO APPROACH')
IF(IS.EQ.0) WRITE(6,102)
102 FORMAT(1, 'THIS RUN IS FOR A STBD SIDE TO APPROACH')
CALL ENDRW(NPLOT)

END
STOP
FORTRAN
INSERT FUNCTION SPDCTR FROM APPENDIX A HERE
INSERT FUNCTION DEGRAD FROM APPENDIX A HERE
INSERT SUBROUTINE TRANS FROM APPENDIX A HERE
INSERT SUBROUTINE HDGRAS FROM APPENDIX A HERE
INSERT SUBROUTINE RBMEAS FROM APPENDIX A HERE
INSERT SUBROUTINE SLOPES FROM APPENDIX A HERE
//G.FT06F001 DD SYSOUT=0,SPACE=(4,1)
//PLCT.SYSIN DD *

```

4

7.0 5.0

4

7.0 5.0

4

7.0 5.0

7

0.0 0.1

7.0 5.0

4

7.0 5.0

4

7.0 5.0

INSERT TWO /\* CARDS HERE

## COMPUTER PROGRAM #6

This program combines the approach and turn phases of computer program #5. The added subroutine is a result of simulation requirements to switch between adaptive gains.

This run produced the plots of figures III-22 thru III-34. By substituting the initial conditions of table III-3, this program produced the plots of figures III-35 thru III-64.

# COMPUTER PROGRAM #6

```

//UHRINTF6 JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=10
// EXEC DSL
//DSL INPUT DD *
* RAS RUDDER CONTROL - APPROACH PHASE FOLLOWED BY TURN PHASE
TITLE RAS RUDDER CONTROL - APPROACH PHASE FOLLOWED BY TURN PHASE
INTEG RKSF
INTEG NFLOT
CONST NPLOT=2
INTEG N,IS
CONST N=1,RD=1.0
* SET IS FOR SIDE OF APPROACH IS=1 PORT, IS=0 STBD
* SET DD FOR DESIRED FINAL LATERAL SEPARATION DESIRED
IS=1,DD=0.2
CONST RSENS=1.86642
PARAM WTSSENS=2.38692
PARAM RGN=23.41847
PARAM VFBG=4.35162
PARAM TSTP1=35.0,TSTP2=36.0
* HYDRODYNAMIC COEFFICIENTS
CONST NR=-0.00227,NV=-0.00351,NVD=-0.000197
CONST MYVD=0.015,MYR=0.0051,I2NRD=0.00068,MXUD=0.0085
CONST YV=-0.01243,XU=-0.0012,YRD=-0.00027
CONST YDEL=-0.0027,NDEL=-0.00126,XDEL=-0.0
CONST DLDM=2.0,DLTEM=7.0
* INITIAL SEPERATION
* SET IC FOR APPROACH TESTING
X01=5.0,Y01=0.0,X02=0.0,Y02=0.4
* INITIAL CONDITIONS
INCCN YAW01=0.0
INCON Y01=0.0,Y02=0.0,YN1=0.0,YN2=0.0
INCON U01=1.0,U02=1.5
INITIAL
DY0=Y02-Y01
DX0=X02-X01
CALL TRANS(YAW01,DX0,DY0,ADX,ADY)
CALL SLOPES(ADX,ADY,Y01,Y02,YN1,YN2)
CALCULATION OF THE COEFFICIENTS
NC1=-XU
NC2=-XU
A11=MYVD
B11=-YV
A21=-YRD
B21=MYR

```

```

A12=-NVD
B12=-NV
A22=IZNRD
B22=-NR
A33=MXUD
B33=-XU
KAI=-YDELR
KBI=XDELR
D=A11*A22-A12*A21
DELRM=41.6953
RDC=180./3.1415926
LUC=20.84765
KG=DLTDM/DLTEM
DIDIC=0.0
D2=DEGRAD(1,1,D2D)
BYG2=0.0
DERIVATIVE
DIDES=5.0*STEP(TSTP1)-5.0*STEP(TSTP2)
DLTSI=LIMIT(-30.0,30.0,DIDES)
DLTEI=DLTSI-DID
DLTBEI=LIMIT(-DLTEM,DLTEM,DLTEI)
DID=INTGRL(DIDIC,KG*DLTBEI*LUC)
DI=DEGRAD(1,1,DID)
DX=X2-X1
DY=Y2-Y1
SIMULATION SHIP A
IF11=KAI*DI
IF21=KBI*DI+NC1
I11=-B11*ADOT1-B21*BDOOT1+IF11
I21=-B12*ADOT1-B22*BDOOT1+IF21
I31=-B33*CDOOT1+IF31
ADDOT1=(I11*A22-I21*A21)/D
BDCOT1=(I21*A11-I11*A12)/D
CDDOT1=I31/A33
ACOT1=INTGRL(0.,ADDOT1)
BCOT1=INTGRL(0.,BDDOT1)
CCOT1=INTGRL(UO1,CDDOT1)
BY1=INTGRL(0.,BDOOT1)
XCOT1=CDOOT1*COS(BY1)-ADOT1*SIN(BY1)
YDCT1=CDOOT1*SIN(BY1)+ADOT1*COS(BY1)
X1=INTGRL(XO1,XDOT1)
Y1=INTGRL(YO1,YDOT1)
YAW1=BY1
SWAY1=Y1
SURGE1=X1

```

\*

```

*
SIMULATION SHIP B
IF12=KA1*D2+YY2
IF22=KB1*D2+YN2
IF32=KC1*D2+NC2
I12=-B11*ADOT2-B21*BDOIT2+IF12
I22=-B12*ADOT2+IF32
I32=-B33*CDOT2+IF32
ACDOT2=(I12*A22-I22*A21)/D
BDDOT2=(I22*A11-I12*A12)/D
CDDOT2=I32/A33
ADOT2=INTGRL(0.,ADDOT2)
BCOT2=INTGRL(0.,BDDOT2)
CDOT2=SPDCTR(ADX,U01,U02)
BY2=INTGRL(BY02,BDOT2)
XDOT2=CDOT2*COS(BY2)-ADOT2*SIN(BY2)
YDOT2=CDOT2*SIN(BY2)+ADOT2*COS(BY2)
X2=INTGRL(X02,XDOT2)
Y2=INTGRL(Y02,YDOT2)
YAW2=BY2
SWAY2=Y2
SURGE2=X2
NOSORT
YAWD1=DEGRAD(0,0,YAW1)
YAWDPI1=DEGRAD(0,1,YAW1)
YAWD2=DEGRAD(0,0,YAW2)
YAWDP2=DEGRAD(0,1,YAW2)
RUDDER RESPONSE INPUT
CALL RBMEAS(N,YAW1,X1,Y1,YAW2,X2,Y2,RD,R1,B1,BB1,R2,B2,BB2)
CALL HDGRAS(N,IS,RI,B1,BB1,R2,B2,BB2,RSENS,YAW2,PSIDFD,PSIADD,...,
PSIDED,WT,DA,AID,B1D,B2D,WTSENS,DD,RD)
BCOT2D=DEGRAD(0,1,BDOT2)
BCOTFB=VF8G*BDOIT2D
DDUMB=YAWD2-PSIDED+BDOITFB
IF(DDUMB.GT.180.0) DDUMB=DDUMB-360.0
IF(DDUMB.LT.-180.0) DDUMB=360.0+DDUMB
DLTS=LIMIT(-30.0,30.0,DDUMB*RGD)
DLTE=DLTS-D2D
DLTBE=LIMIT(-DLTEM,DLTE)
D2D=INTGRL(D2DIC,KG*DLTBE*LUC)
D2=DEGRAD(1,1,D2D)
SORT
DSTE=ABS(DD-ADY)
OBJ=INTGRL(0.0,DISTE)
DYNAMIC REGION
*
ACTUAL SEPARATION
DX=X2-X1
DY=Y2-Y1
CALL TRANS(YAW1,DX,DY,ADX,ADY)

```

```

*      EXTERNAL FORCES ACTING BETWEEN SHIPS
      CALL SLOPES(ADX,ADY,Y1,Y2,YN1,YN2)
      IF((ABS(ADY).LT.0.04744).AND.(ABS(ADX).LT.1.0)) WRITE(6,100)
100    FFORMAT(, ****SEPARATION LESS THAN 25 FEET - COLLISION****)
*      ACTUAL TIME CONVERSION (SEC)
      ATIME=LUC*TIME
      AAI=(BB1+BB2)/2.0
      CALL SWITCH(DD,DA,AA1,IS,RSENS,WTSENS,RGN,VFBG,BDOT2D)

SAMPLE  FINTIM=30.,DELT=0.04,DELS=0.04
CONTRL  0.20,X1,X2,DA,AID,PSIDFD,Y1,Y2,R1,BID,PSIADD,YAWD1,YAWD2,R2,...
PRINT   B2D,PSIDED,ATIME,D2D,ADX,DID,YY2,BDOTFB,DLTS,ADY,DLTS1,...

PRPLCT  YN2,CDOOT1,CDOOT2,OBJ,RSENS,VFBG
        CNLY
        CALL DRWG(1,1,ATIME,YAWDP2)
        CALL DRWG(1,2,ATIME,YAWDP1)
        CALL DRWG(2,1,ATIME,YY2)
        CALL DRWG(3,1,ATIME,YN2)
        CALL DRWG(4,1,SURGE2,SWAY2)
        CALL DRWG(4,2,SURGE1,SWAY1)
        CALL DRWG(5,1,ATIME,ADY)
        CALL DRWG(6,1,ATIME,DLTS)
        CALL DRWG(6,2,ATIME,D2D)

TERMINAL
101    IF(IS.EQ.1) WRITE(6,101)
      IF(, THIS RUN IS FOR A PORT SIDE TO APPROACH' )
102    IF(IS.EQ.0) WRITE(6,102)
      IF(, THIS RUN IS FOR A STBD SIDE TO APPROACH' )
      CALL ENDRW(NPLOT)
      CALL CONTIN
      FINTIM=45.0

END
STOP
FORTRAN
INSERT  SUBROUTINE SWITCH FROM APPENDIX A HERE
INSERT  FUNCTION SPDCTR FROM APPENDIX A HERE
INSERT  FUNCTION DEGRAD FROM APPENDIX A HERE
INSERT  SUBROUTINE TRANS FROM APPENDIX A HERE
INSERT  SUBROUTINE HDGRAS FROM APPENDIX A HERE
INSERT  SUBROUTINE RBMEAS FROM APPENDIX A HERE
INSERT  SUBROUTINE SLOPES FROM APPENDIX A HERE
//FLCT.SYSIN DD *

```

4

4

7.0 5.0

7.0 5.0

4 7 4 4 4 4 4 7 4 4

7.0	5.0
7.0	5.0
7.0	5.0
7.0	5.0
7.0	5.0
7.0	5.0
7.0	5.0
7.0	5.0
7.0	5.0
7.0	5.0
7.0	5.0
7.0	5.0

0.0 0.1

-2.0 0.5

INSERT TWO /\* CARDS HERE

## COMPUTER PROGRAM #7

This program combines the calm sea simulation of computer program #6 with the wave simulation of computer program #4 to simulate the model and control system in a sea state. The waves are introduced thru the rudder nondimensionalized coefficients as shown in chapter II.

The plots produced are shown in figures III-66 thru III-73. Figure III-65 was produced with the same program by setting  $W1=1.5$ .

# COMPUTER PROGRAM #7

```

//UHRINTF7 JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=10
//EXEC DSL
//DSL.INPUT DD *
* TITLE RAS RUDDER CONTROL - SIMULATION WITH WAVE PERTURBATIONS
* RAS RUDDER CONTROL - SIMULATION WITH WAVE PERTURBATIONS
INTEGER NIS
CONST N=1, RD=1.0
PARAM IS=1, DD=0.2
PARAM RSENS=1.86642
PARAM WTSENS=2.38692
PARAM RGN=23.41847
PARAM VFBC=4.35162
PARAM TSTP1=35.0, TSTP2=36.0
* HYDRODYNAMIC COEFFICIENTS
CONST MYVD=-0.00227, NV=-0.00351, NVD=-0.000197
CONST YV=-0.015, MYR=0.0051, IZNRD=0.00068, MXUD=0.0085
CONST YDEL=-0.0027, NDEL=-0.0012, YRD=-0.00027
CONST DLTD=2.0, DLTDM=7.0
* INITIAL SEPERATION
INCON X01=5.0, Y01=0.0, X02=0.0, Y02=0.4
* INITIAL CONDITIONS
INCON YAW01=0.0
INCON Y01=0.0, Y02=0.0, YN1=0.0, YN2=0.0
INCON U01=1.0, U02=1.5
PARAM WS=5.0
PARAM WD=-0.15
PARAM WL=1.0
PARAM WFMA=0.05685
INITIAL
DY0=Y02-Y01
DX0=X02-X01
CALL TRANS(YAW01, DX0, DY0, ADX, ADY)
CALL SLOPES(ADX, ADY, Y01, Y02, YN1, YN2)
CALCULATION OF THE COEFFICIENTS
NC1=-XU
NC2=-XU
A11=MYVD
B11=-YV
A21=-YRD

```

\*

```

B21=MYR
A12=-NVD
B12=-NV
A22=IZNRD
B22=-NR
A33=MXUD
B33=-XU
KAI=-YDELR
KBI=NDELR
KCI=XDELR
D=A11*A22-A12*A21
DELRM=41.6953
RDC=180./3.1415926
DRC=3.1415926/180.
LUC=20.84765
KG=DLTDM/DLTEM
DIDIC=0.0
D2=DEGRAD(1,1,D2D)
BY02=0.0
DERIVATIVE
WFI=(WFMA/(0.1137*40.0))*RAMP(0.0)
WF=LIMIT((-WFMA,WFMA,WFI)
WRV=NORMAL(1975,0.0,WFMA/10.0)
WV=WS/15.0
EWD=WD-YAWDP2
EWD=DEGRAD(1,1,EWDD)
WEF=2.0*3.1415926*(C DOT T2+WV*COS(EWD))/WL
WE=WEF*TIME
WFI=WF*SIN(EWD)
WFN=WF*SIN(2.0*EWD)
WFX=WF*COS(EWD)
WNF=WFN*SIN(WE)+(3.1415926*WFX**2/WL)*SIN(2.0*WE)
WXF=WFX*SIN(WE)+(3.1415926*WFX**2/WL)*SIN(2.0*WE)
WY=WYF+WRV*WFX*SIN(WE)
WN=WNF+WRV*WFX*SIN(WE)
WX=WXF+WRV*WFX*SIN(WE)
DIDES=5.0*STEP(TSTP1)-5.0*STEP(TSTP2)
DLTSI=LIMIT(-30.0,30.0,DIDES)
DLTEI=DLTSI-DID
DLTBEI=LIMIT(-DLTEM,DLTEM,DLTEI)
DID=INTGRL(DIDIC,KG*DLTBEI*LUC)
D1=DEGRAD(1,1,DID)
DX=X2-X1
DY=Y2-Y1
SIMULATION SHIP A
IF1=KAI*DI
IF21=KBI*DI

```

\*

```

IF31=KC1*DI+NC1
I11=-B11*ADOT1-B21*BDOOT1+IF11
I21=-B12*ADOT1-B22*BDOOT1+IF21
I31=-B33*CDOT1+IF31
ADDOT1=(I11*A22-I21*A21)/D
BDDOT1=(I21*A11-I11*A12)/D
CDDOT1=I31/A33
ACOT1=INTGRL(0.,ADDOT1)
BCOT1=INTGRL(0.,BDDOT1)
CDOT1=INTGRL(U01,CDDOT1)
BY1=INTGRL(0.,BDOOT1)
XDOT1=CDOT1*COS(BY1)-ADOT1*SIN(BY1)
YDOT1=CDOT1*SIN(BY1)+ADOT1*COS(BY1)
X1=INTGRL(X01,XDOT1)
Y1=INTGRL(Y01,YDOT1)
YAW1=BY1
SWAY1=Y1
SURGE1=X1
SIMULATION SHIP B
IF12=KA1*D2+YY2+KA1*WY
IF22=KB1*D2+YN2+KB1*WN
IF32=KC1*D2+NC2+KC1*WX
I12=-B11*ADOT2-B21*BDOOT2+IF12
I22=-B12*ADOT2-B22*BDOOT2+IF22
I32=-B33*CDOT2+IF32
ADDOT2=(I12*A22-I22*A21)/D
BDDOT2=(I22*A11-I12*A12)/D
CDDOT2=I32/A33
ADOT2=INTGRL(0.,ADDOT2)
BDOT2=INTGRL(0.,BDDOT2)
CDOT2=SPDC TR(ADX,U01,U02)
BY2=INTGRL(BY02,BDOT2)
XDOT2=CDOT2*COS(BY2)-ADOT2*SIN(BY2)
YDOT2=CDOT2*SIN(BY2)+ADOT2*COS(BY2)
X2=INTGRL(X02,XDOT2)
Y2=INTGRL(Y02,YDOT2)
YAW2=BY2
SWAY2=Y2
SURGE2=X2

```

NOSORT

```

YAWD1=DEGRAD(0,0,YAW1)
YAWDP1=DEGRAD(0,1,YAW1)
YAWD2=DEGRAD(0,0,YAW2)
YAWDP2=DEGRAD(0,1,YAW2)
YAWDPD=YAWDP1-YAWDP2
RUDDER RESPONSE INPUT
CALL RBMEAS(N,YAW1,X1,Y1,YAW2,X2,Y2,RO,R1,B1,BB1,R2,B2,BB2)
CALL HDGRAS(N,IS,R1,B1,BB1,R2,B2,BB2,RSENS,YAW2,PSIADD,...

```

\*

\*



```
CALL ENDRW(NPLOT)
CALL CONTIN
FINTIM=45.0
```

```
END
STOP
FORTRAN
INSERT SUBROUTINE SWITCH FROM APPENDIX A HERE
INSERT FUNCTION SPDCTR FROM APPENDIX A HERE
INSERT FUNCTION DEGRAD FROM APPENDIX A HERE
INSERT SUBROUTINE TRANS FROM APPENDIX A HERE
INSERT SUBROUTINE HDGRAS FROM APPENDIX A HERE
INSERT SUBROUTINE RBMEAS FROM APPENDIX A HERE
INSERT SUBROUTINE SLOPES FROM APPENDIX A HERE
//PLOT.SYSIN DD *
```

7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4

```
INSERT TWO /* CARDS HERE
```

## COMPUTER PROGRAM #8

This program incorporates a fifth order polynomial curve fit speed control switching function to give optimal longitudinal positioning. The scenario is the same that was used in the design of the heading control development. The low order model of the gas turbine propulsion plant was used.

The plots produced are shown in figures III-80 thru III-83.

# COMPUTER PROGRAM #8

```

//UHRINTF8 JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=10
//EXEC DSL
//DSL INPUT DD *
* TITLE RAS SPEED CONTROL - CONTROL TESTING
INTEGER NPLT=2
INTEGER NIS=1
CONST N=1, RD=1.0
PARAM IS=1, DD=0.2
PARAM RSENS=1.86642
PARAM WTSENS=2.38692
PARAM WGN=23.41847
PARAM VFEG=4.35162
PARAM TSTP1=35.0, TSTP2=36.0
* HYDRODYNAMIC COEFFICIENTS
CONST NR=-0.00227, NV=-0.00351, NVD=-0.000197
CONST MYVD=0.015, MYR=0.0051, IZNRD=0.00068, MXUD=0.0085
CONST YV=-0.01243, XU=-0.0012, YRD=-0.00027
CONST YDELRL=-0.0027, NDELR=-0.00126, XDELR=0.0
CONST DLITDM=2.0, DLITEM=7.0
* INITIAL SEPERATION
INCON X01=5.0, Y01=0.0, X02=0.0, Y02=0.4
* INITIAL CONDITIONS
INCON YAW01=0.0
INCON YY1=0.0, YY2=0.0, YN1=0.0, YN2=0.0
INCON U01=1.0, U02=1.5
PARAM UF=21.73, A=22.0, G=0.092
INITIAL
Y0=Y02-Y01
DX0=X02-X01
CALL TRANS(YAW01, DX0, DY0, ADX, ADY)
CALL SLOPES(ADX, ADY, YY1, YY2, YN1, YN2)
CALCULATION OF THE COEFFICIENTS
NC1=-XU
NC2=-XU
A11=MYVD
B11=-YV
A21=-YRD
B21=-MYR
A12=-NVD
B12=-NV

```

\*

```

A22=IZNRD
B22=-NR
A33=MXUD
B33=-XU
KAI=-YDELR
KB1=NDELR
KC1=XDELR
D=A11*A22-A12*A21
DELRM=41.6953
RDC=180./3.1415926
LUC=20.84765
KG=DLTDM/DLTEM
DLDIC=0.0
C2=DEGRAD(1,1,D2D)
BY02=0.0
K=UF/A
P=4.88/LUC
SPDDER=U01/K
DERIVATIVE
DIDES=5.0*STEP(TSTP1)-5.0*STEP(TSTP2)
DLTSL=LIMIT(-30.0,30.0,DIDES)
DLTEI=DLTSL-D1D
DLTBEI=LIMIT(-DLTEM,DLTEM,DLTEI)
D1D=INTGRL(D1DIC,KG*DLTBEI*LUC)
D1=DEGRAD(1,1,D1D)
DX=X2-X1
DY=Y2-Y1
SIMULATION SHIP A
IF11=KA1*D1
IF21=KB1*D1+NC1
IF31=KC1*D1+NC1
I11=-B11*ADOT1-B21*BDO11+IF11
I21=-B12*ADOT1-B22*BDO11+IF21
I31=-B33*CDOT1+IF31
ADOT1=(I11*A22-I21*A21)/D
BDOT1=(I21*A11-I11*A12)/D
CDOT1=I31/A33
ACOT1=INTGRL(0.,ADOT1)
BCOT1=INTGRL(0.,BDOT1)
CCOT1=INTGRL(U01,CDOT1)
BY1=INTGRL(0.,BDOT1)
XDOT1=CDOT1*COS(BY1)-ADOT1*SIN(BY1)
YDOT1=CDOT1*SIN(BY1)+ADOT1*COS(BY1)
X1=INTGRL(X01,XDOT1)
Y1=INTGRL(Y01,YDOT1)
YAW1=BY1
SWAY1=Y1

```

\*

```

*
SURGE1=X1
SIMULATION SHIP B
IF12=KA1*Y2+YN2
IF22=KB1*Y2+YN2
IF32=KC1*Y2+YN2
IF12=-B11*ADOT2-B22*BDOT2+IF12
IF22=-B12*ADOT2-B22*BDOT2+IF22
IF32=-B13*ADOT2-B22*BDOT2+IF32
ADDOT2=(I12*A22-I22*A21)/D
BDOT2=(I12*A21-I12*A12)/D
CDDOT2=I32/A33
ACDOT2=INTGRL(0.,ADDOT2)
BCDOT2=INTGRL(0.,BDDOT2)
SW=SWCL(U01,U02)
SPDDEL=SPDRCL(ADX,U01,U02,SW)
SPDDEL=DELAY(7,P,(SPDDEL/K-SPDDEL))
SPDEL=SPINIT(SPDEL,TIME,(SPDDEL/K-SPDDEL))
SPCIN=K*(SPDEL+SPDDEL)
SPDERR=(SPDIN-CDDOT2)*G
CDDOT2=INTGRL(U02,SPDERR*LUC)
BY2=INTGRL(BY02,BDDOT2)
XDDOT2=CDDOT2*COS(BY2)-ADDOT2*SIN(BY2)
YDDOT2=CDDOT2*SIN(BY2)+ADDOT2*COS(BY2)
X2=INTGRL(X02,XDDOT2)
Y2=INTGRL(Y02,YDDOT2)
YAW2=BY2
SWAY2=Y2
SURGE2=X2
NOSORT
YAWD1=DEGRAD(0,0,YAW1)
YAWDPI1=DEGRAD(0,1,YAW1)
YAWD2=DEGRAD(0,0,YAW2)
YAWDP2=DEGRAD(0,1,YAW2)
YAWDPD=YAWDP1-YAWDP2
RUDDER RESPONSE INPUT
CALL RBMEAS(N,YAW1,X1,Y1,YAW2,X2,Y2,RD,R1,B1,BB1,R2,B2,BB2)
CALL PDGRAS(N,IS,R1,B1,BB1,R2,B2,BB2,RSENS,YAW2,PSIDFD,PSIADD,...)
PSIDED,WT,DA,AID,BID,B2D,WTSENS,DD,RD)
BCDOT2=DEGRAD(0,1,BDDOT2)
BCOTFB=VFBG*BDOT2D
DDUMB=YAWD2-PSIDED+BDOTFB
IF(DDUMB.GT.180.0) DDUMB=DDUMB-360.0
IF(DDUMB.LT.-180.0) DDUMB=DDUMB+360.0+DDUMB
DLTS=LIMIT(-30.0,30.0,DDUMB*RGN)
DLTE=DLTS-D2D
DLTBE=LIMIT(-DLT=M,DLTE,M,DLTBE*LUC)
D2D=INTGRL(D2D,DIC,KG*DLTBE*LUC)
D2=DEGRAD(1,1,D2D)
*

```

```

SORT
DISTE=ABS(DD-ADY)
OBJJ=INTGRL(0.0,DISTE)
DISTES=ABS(ADX)
OBJJS=INTGRL(0.0,DISTES/25.0)
DYNAMIC REGION ACTUAL SEPARATION
*
DX=X2-X1
DY=Y2-Y1
CALL TRANS(YAW1,DX,DY,ADX,ADY)
EXTERNAL FORCES ACTING BETWEEN SHIPS
CALL SLOPES(ADX,ADY,YY1,YY2,YN1,YN2)
IF((ABS(ADY).LT.0.04744).AND.(ABS(ADX).LT.1.0)) WRITE(6,100)
100 FORMAT(' *****SEPARATION LESS THAN 25 FEET - COLLISION*****')
*
ACTUAL TIME CONVERSION (SEC)
ATIME=LUC*TIME
AA1=(BB1+BB2)/2.0
CALL SWITCH(DD,DA,AA1,IS,RSENS,MTSENS,RGN,VFBG,BDOT2D)
SAMPLE FINTIM=30.,DELT=0.04,DELS=0.04
CONTROL 0.20,ATIME,ADX,ADY,YAWD1,YAWD2,YAWDPD,SPDDES,CDOT2
PRINT PRPLOT ONLY
CALL DRWG(1,1,ATIME,ADX)
CALL DRWG(2,1,ATIME,SPDDES)
CALL DRWG(2,2,ATIME,CDOT2)
TERMINAL
IF (IS.EQ.1) WRITE(6,101)
101 FORMAT(' THIS RUN IS FOR A PORT SIDE TO APPROACH')
IF (IS.EQ.0) WRITE(6,102)
102 FORMAT(' THIS RUN IS FOR A STBD SIDE TO APPROACH')
CALL ENDRW(NPLOT)
CALL CONTIN
FINTIM=45.0
END
STOP
FORTRAN
INSERT SUBROUTINE RBMEAS FROM APPENDIX A HERE
INSERT SUBROUTINE HDGRAS FROM APPENDIX A HERE
INSERT FUNCTION DEGRAD FROM APPENDIX A HERE
INSERT SUBROUTINE TRANS FROM APPENDIX A HERE
INSERT SUBROUTINE SWTCH FROM APPENDIX A HERE
INSERT FUNCTION SWCL FROM APPENDIX A HERE
INSERT FUNCTION SPDREC FROM APPENDIX A HERE
INSERT FUNCTION SPINIT FROM APPENDIX A HERE
INSERT SUBROUTINE SLOPES FROM APPENDIX A HERE
//PLOT.SYSIN CD

```

7.0	5.0
7.0	5.0
7.0	5.0
7.0	5.0

4
4
4

INSERT TWO /\* CARDS HERE

## COMPUTER PROGRAM #9

This program introduces a longitudinal position offset capability. The method takes the control ship to the alongside position until 450 seconds into the run. After that time, with the ship steadied, the offset position desired (XCFSD) is switched to the desired offset. This method negates some of the transient oscillations which cause unstable conditions in the approach phase. A secondary change is the use of subroutine SWTCHF instead of subroutine SWTCH developed in the heading control section. This new subroutine relaxes the heading velocity feedback gain (VFEG) to allow turn stability in the turn phase.

The plots produced by this program are shown in figures III-84 thru III-101.

# COMPUTER PROGRAM #9

```

//UHRINTF9 JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=10
// EXEC DSL
//DSL INPUT DO *
* TITLE RAS SPEED CONTROL - OFFSET TESTING
* INTEG RKSFX
INTEG RNPLOT
CONST NPLOT=2
INTEG N1 IS
CONST N=1, RD=1.0
PARAM IS=1, DD=0.2
PARAM RSENS=1.86642
PARAM WSENS=2.38692
PARAM RGN=23.41847
PARAM VFBG=4.35162
PARAM TSTP1=35.0, TSTP2=36.0
* HYDRODYNAMIC COEFFICIENTS
CONST MYVD=0.00227, NV=-0.00351, NVD=-0.000197
CONST MYVD=0.015, MYR=0.0051, IZNRD=0.00068, MXUD=0.0085
CONST YV=-0.01243, XU=-0.0012, YRD=-0.00027
CONST YDELRL=-0.0027, NDELR=-0.00126, XDELR=0.0
CONST DLTDLM=2.0, DLTDEM=7.0
* INITIAL SEPERATION
INCON X01=5.0, Y01=0.0, X02=0.0, Y02=0.4
* INITIAL CONDITIONS
INCON YAW01=0.0, YN1=0.0, YN2=0.0
INCON U01=1.0, U02=1.5
INCON X0FS IS THE DESIRED NORMALIZED X POSITION / 0.0 IS ALONGSIDE /
* * * * * X0FS NEG FOR ASTERN OF ALONGSIDE / POS FOR FWD OF ALONGSIDE
* * * * * NOTE - X0FS CAN BE USED FOR VEHICLE OF APPROACH AND EXIT FROM
* * * * * STATION BY SETTING SOME DESIRED POSITION EG. -5.0, 5.0
* * * * * THIS WOULD CAUSE APPROACH OR BREAK AWAY STATION ATTAINMENT
* * * * * WHICH CAN BE PRECEDED BY OR FOLLOWED BY NON RAS POSITION
* * * * * CONTROL
PARAM XGFS=0.0
PARAM XCFSD=0.0
PARAM UF=21.73, A=22.0, G=0.092
INITIAL
DY0=Y02-Y01
DX0=X02-X01
CALL TRANS(YAW01, DX0, DY0, ADX, ADY)
CALL SLOPES(ADX, ADY, Y01, Y02, YN1, YN2)

```

\*

CALCULATION OF THE COEFFICIENTS

NC1=-XU  
NC2=-XU  
A11=MYVD  
B11=-YV  
A21=-YRD  
B21=MYR  
A12=-NVC  
B12=-NV  
A22=IZNRD  
B22=-NR  
A33=MXUD  
B33=-XU  
KA1=-YDELR  
KB1=NDELR  
KC1=XDELR  
D=A11\*A22-A12\*A21  
DELRM=41.6953  
RCC=180./3.1415926  
CRC=3.1415926/180.  
LUC=20.84765  
KG=CLTCM/DLTEM  
DIDIC=0.0  
D2=DEGRAD(1,1,D2D)  
BY02=0.0  
K=UF/A  
P=4.88/LUC  
SPC01=1.0  
SPD02=1.5  
SPDDER=SPD01/K

DERIVATIVE

DIDES=5.0\*STEP(TSTP1)-5.0\*STEP(TSTP2)  
DLTSL=LIMIT(-30.0,30.0,DIDES)  
DLTBE1=DLTSL-DID  
CLTBE1=LIMIT(-DLTEM,DLTEM,DLTBE1)  
DID=INTGRL(DIDIC,KG\*DLTBE1\*LUC)  
CI=DEGRAD(1,1,DID)  
DX=X2-X1  
DY=Y2-Y1

\*

SIMULATION SHIP A  
IF11=KA1\*D1  
IF21=KB1\*D1  
IF31=KC1\*D1+NC1  
I11=-B11\*ADOT1-B21\*BDOOT1+IF11  
I21=-B12\*ADOT1-B22\*BDOOT1+IF21  
I31=-B33\*CDOT1+IF31  
ACDOT1=(I11\*A22-I21\*A21)/D  
BDOOT1=(I21\*A11-I11\*A12)/D

```

CCDOT1=I31/A33
ACDOT1=INTGRL(O.,ADDOT1)
BCDOT1=INTGRL(O.,BDDOT1)
CCDOT1=INTGRL(U01,CDDOT1)
BY1=INTGRL(O.,BDDOT1)
XDOT1=CDDOT1*COS(BY1)-ADOT1*SIN(BY1)
YDOT1=CDDOT1*SIN(BY1)+ADOT1*COS(BY1)
X1=INTGRL(X01,XDOT1)
Y1=INTGRL(Y01,YDOT1)
YAW1=BY1
SWAY1=Y1
SURGE1=X1
SIMULATION SHIP B
IF12=KAL*D2+YY2
IF22=KB1*D2+YN2
IF32=KC1*D2+NC2
I12=-B11*ADOT2-B21*BDDOT2+IF12
I22=-B12*ADOT2+IF22
I32=-B13*ADOT2+IF32
ACDOT2=(I12*A22-I22*A21)/D
BDDOT2=(I12*A12-I22*A11)/D
CCDOT2=I32/A33
ADOT2=INTGRL(O.,ADDOT2)
BCDOT2=INTGRL(O.,BDDOT2)
SW=SWCL(SPDOT1,SPDOT2)
SPDDES=SPDOFC(ADX,SPDOT1,SPDOT2,SW,XOFS)
SPDELC=DELAY(7,P,(SPDDES/K-SPDDER))
SPDEL=SPINIT(SPDEL,TIME,(SPDES/K-SPDDER))
SPDIN=K*(SPDEL+SPDDER)
SPDERR=(SPDIN-CDDOT2)*G
CCOT2=INTGRL(U02,SPDERR*LUC)
BY2=INTGRL(BY02,BDOT2)
XDOT2=CDDOT2*COS(BY2)-ADOT2*SIN(BY2)
YDOT2=CDDOT2*SIN(BY2)+ADOT2*COS(BY2)
X2=INTGRL(X02,XDOT2)
Y2=INTGRL(Y02,YDOT2)
YAW2=BY2
SWAY2=Y2
SURGE2=X2
NOSORT
YAWD1=DEGRAD(O.,YAW1)
YAWCP1=DEGRAD(O.,YAW1)
YAWD2=DEGRAD(O.,YAW2)
YAWCP2=DEGRAD(O.,YAW2)
YAWDPD=YAWDP1-YAWDP2
RUDDER RESPONSE INPUT
CALL RBMEAS(N,YAW1,X1,Y1,YAW2,X2,Y2,RD,R1,B1,BB1,R2,B2,BB2)
CALL HDGRAS(N,IS,R1,B1,BB1,R2,B2,BB2,PSIDFD,PSIADD,...

```

\*

\*

```

PSIDED,WT,DA,AID,B1D,B2D,WTSENS,DD,RD)
BCOT2D=DEGRAD(0,1,BDOT2)
BCOTFB=VF8G*BDOT2D
DCUMB=YAWD2-PSIDED+BDOTFB
IF(DDUMB.GT.180.0) DDUMB=DDUMB-360.0
IF(DDUMB.LT.-180.0) DDUMB=360.0+DDUMB
DLTS=LIMIT(-30.0,30.0,DDUMB*RGN)
DLTE=DLTS-D2D
DLTBE=LIMIT(-DLTEM,DLTEM,DLTE)
D2C=INTGRL(D2DIC,KG*DLTBE*LUC)
D2=DEGRAD(1,1,D2D)

SORT
DISTE=ABS(DD-ADY)
CBJ=INTGRL(0.0,DISTE)
DISTES=ABS(ADX)
OBJJS=INTGRL(0.0,DISTES/25.0)

DYNAMIC REGION
* ACTUAL SEPARATION
DX=X2-X1
DY=Y2-Y1
CALL TRANS(YAW1,DX,DY,ADX,ADY)
EXTERNAL FORCES ACTING BETWEEN SHIPS
CALL SLOPES(ADX,ADY,Y1,Y2,YN1,YN2)
IF(ABS(ADY).LT.0.04744).AND.(ABS(ADX).LT.1.0)) WRITE(6,100)
100 FORMAT(' *****SEPARATION LESS THAN 25 FEET - COLLISION*****')
* ACTUAL TIME CONVERSION (SEC)
ATIME=LUC*TIME
AA1=(BB1+BB2)/2.0
CALL SWITCHF(DD,DA,AA1,IS,RSENS,WTSENS,RGN,VFBG,BDOT2D,XOFS)
IF (ATIME.GT.450.0) XOFS=XOFSD

SAMPLE FINIM=30.,DELT=0.04,DELS=0.04
CONTRL 0.20,ATIME,ADX,ADY,YAWD1,YAWD2,YAWDPD,SPDDDES,CDOT2
PRPLOT ONLY
CALL DRWG(1,1,ATIME,ADY)
CALL DRWG(2,1,ATIME,YAWDPD)
CALL DRWG(3,1,ATIME,SPDDDES)
CALL DRWG(3,2,ATIME,CDOT2)
CALL DRWG(4,1,ATIME,ADX)

TERMINAL
IF(IS.EQ.1) WRITE(6,101)
101 FORMAT(' THIS RUN IS FOR A PORT SIDE TO APPROACH')
102 FORMAT(' THIS RUN IS FOR A STBD SIDE TO APPROACH')
CALL ENDRW(NPLOT)
CALL CONTIN
FINIM=45.0
END

```

```

STOP
FORTRAN
  SUBROUTINE RBMEAS FROM APPENDIX A HERE
  SUBROUTINE HDGRAS FROM APPENDIX A HERE
  FUNCTION DEGRAD FROM APPENDIX A HERE
  SUBROUTINE TRANS FROM APPENDIX A HERE
  SUBROUTINE SWTCHF FROM APPENDIX A HERE
  FUNCTION SWCL FROM APPENDIX A HERE
  FUNCTION SPDOFC FROM APPENDIX A HERE
  FUNCTION SPINIT FROM APPENDIX A HERE
  SUBROUTINE SLOPES FROM APPENDIX A HERE
  //PLOT.SYSIN DD *

```

7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4
7.0	5.0	4

```

INSERT TWO /* CARDS HERE

```

## COMPUTER PROGRAM #10

This program incorporates the sea state first programmed in computer programs #4 and #7. The WX wave force, however, is introduced at the end of the propulsion loop to allow more realistic perturbations. This is the final form of the complete heading and speed control systems. To run this without a sea state, set WFMA to 0.0.

This program produced the plots shown in figures III-103 thru III-105.

# COMPUTER PROGRAM #10

```

//UHRINTFO JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=5
//EXEC DSL
//DSL INPUT DD *
* RAS SPEED CONTROL - WAVE INTERACTION
* RAS SPEED CONTROL - WAVE INTERACTION
TITLE RKSFX
INTEG RKSFX
INTEG NPLT=2
CONST NPLT=2
INTEG NPLT=2
CONST NPLT=2
PARAM NPLT=2
PARAM RSENS=2.38692
PARAM WTSENS=2.38692
PARAM RFBG=4.35162
PARAM TSTPI=35.0
PARAM HYDRODYNAMIC COEFFICIENTS
CONST MYVD=-0.00227,NV=-0.00351,NVD=-0.000197
CONST MYV=-0.015,MYR=-0.0051,IZNRD=0.00068,MXUD=0.0085
CONST YV=-0.01243,XU=-0.0012,YRD=-0.00027
CONST YDEL=-0.00027,NDEL=-0.00126,XDEL=-0.0
CONST DLTD=2.0,DLTEM=7.0
* INITIAL SEPARATION
INCON X01=5.0,Y01=0.0,X02=0.0,Y02=0.4
* INITIAL CONDITIONS
INCON YAW01=0.0
INCON Y01=0.0,Y02=0.0,YN2=0.0
INCON X01=1.0,U02=1.5
XOFS IS THE DESIRED NORMALIZED X POSITION / 0.0 IS ALONGSIDE /
NEG FOR ASTERN OF ALONGSIDE / POS FOR FWD OF ALONGSIDE /
NOTE - XOFS CAN BE USED FOR VEHICLE OF APPROACH AND EXIT FROM
STATION BY SETTING SOME DESIRED POSITION EG. -5.0, 5.0
THIS WOULD CAUSE APPROACH OR BREAK AWAY STATION ATTAINMENT
WHICH CAN BE PRECEDED BY OR FOLLOWED BY NON RAS POSITION
CONTROL
PARAM XQFS=0.0
PARAM XQFSD=0.0
PARAM UF=21.73,A=22.0, G=0.092
PARAM WS=5.0
PARAM WD=-0.15.0
PARAM WL=1.0
PARAM WFMA=0.05685
PARAM KS2=-1.0

```

```

INITIAL
Y0=Y02-X01
DX0=X02-X01
CALL TRANS(YAW01,DX0,DY0,ADX,ADY)
CALL SLOPES(ADX,ADY,YY1,YY2,YN1,YN2)
CALCULATION OF THE COEFFICIENTS
NC1=-XU
NC2=-XU
A11=MYVD
B11=-YV
A21=-YRD
B21=MYR
A12=-NVD
B12=-NV
A22=IZNRD
B22=-NR
A33=MXUD
B33=-XU
KAI=-YDELR
KBI=XDELR
D=A11*A22-A12*A21
DELRM=41.6953
RDC=180./3.1415926
LUC=20.84765
KG=DLTDM/DLTEM
D1DIC=0.0
D2=DEGRAD(1,1,D2D)
BY02=0.0
K=UF/A
P=4.88/LUC
SPD01=1.0
SPD02=1.5
SPDDER=SPD01/K
DERIVATIVE
WFI=(WFMA/(0.1137*40.0))*RAMP(0.0)
WFLIMIT=(-WFMA,WFMA,WFI)
WRV=NORMAL(1975,0.0,WFMA/10.0)
WV=WS/15.0
EWCD=WD-YA WDP2
EWD=DEGRAD(1,1,EWDD)
WEF=2.0*3.1415926*(CDOT2+WV*COS(EWD))/WL
WE=WEF*TIME
WFI=WF*SIN(EWD)
WFN=WF*SIN(2.0*EWD)
WFX=WF*COS(EWD)
WYF=WFY*SIN(WE)+(3.1415926*WFY**2/WL)*SIN(2.0*WE)

```

```

WNF=WFN*(WE)+(3.1415926**WFN**2/WL)*SIN(2.0**WE)
WXF=WFN*(WE)+(3.1415926**WFN**2/WL)*SIN(2.0**WE)
WY=WFN*(WE)+(3.1415926**WFN**2/WL)*SIN(2.0**WE)
WN=WFN*(WE)+(3.1415926**WFN**2/WL)*SIN(2.0**WE)
WX=WFN*(WE)+(3.1415926**WFN**2/WL)*SIN(2.0**WE)
DIDES=5.0*STEP(TSTP1)-5.0*STEP(TSTP2)
DLTS1=LIMIT(-30.0,30.0,DIDES)
DLTE1=DLTS1-DID
DLTBE1=LIMIT(-DLTEM,DLTEM,DLTE1)
DID=INTGRL(DIDIC,KG*DLTBE1*LUC)
DI=DEGRAD(1,1,DID)
DX=X2-X1
DY=Y2-Y1
SIMULATI=ON SHIP A
IF11=KAI*DI
IF21=KBI*DI
IF31=KCI*ABS(DI)+NC1
I11=-B11*ADOT1-B21*BDDOT1+IF11
I21=-B12*ADOT1-B22*BDDOT1+IF21
I31=-B13*ADOT1-B23*BDDOT1+IF31
ACDOT1=(I11*A22-I21*A21)/D
BCDOT1=(I21*A11-I11*A12)/D
CDDOT1=I31/A33
ADCT1=INTGRL(0.,ADDOT1)
BCOT1=INTGRL(0.,BDDOT1)
COT1=INTGRL(U01,CDDOT1)
BY1=INTGRL(0.,BDDOT1)
XDOT1=CDDOT1*COS(BY1)-ADOT1*SIN(BY1)
YDOT1=CDDOT1*SIN(BY1)+ADOT1*COS(BY1)
X1=INTGRL(X01,XDOT1)
Y1=INTGRL(Y01,YDOT1)
YAW1=BY1
SWAY1=Y1
SURGE1=X1
SIMULATI=ON SHIP B
IF12=KAI*D2+YY2+KAI*WY
IF22=KBI*D2+YN2+KBI*WN
IF32=KCI*ABS(D2)+NC2
I12=-B11*ADOT2-B21*BDDOT2+IF12
I22=-B12*ADOT2-B22*BDDOT2+IF22
ADDOT2=(I12*A22-I22*A21)/D
BDDOT2=(I22*A11-I12*A12)/D
ADOT2=INTGRL(0.,ADDOT2)
BCOT2=INTGRL(0.,BDDOT2)
SW=SWCL(SPD01,SPD02)
SPDDES=SPD0FC(ADX,SPD01,SPD02,SW,XOFS)
SPDDEL=DELAY(7,P,(SPDDES/K-SPDDES))
SPDEL=SPINIT(SPDDEL,TIME,(SPDDES/K-SPDDES))

```

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```

SPDIN=K*(SPDEL+SPDDER)
SPDERR=(SPDIN-CDOT2)*G
CDOT2 = INTGRL(U02,SPDERR*LUC)+KS2*WX
BY2=INTGRL(BY02,BDOT2)
XDOT2=CDOT2*COS(BY2)-ADOT2*SIN(BY2)
YDOT2=CDOT2*SIN(BY2)+ADOT2*COS(BY2)
X2=INTGRL(X02,XDOT2)
Y2=INTGRL(Y02,YDOT2)
YAW2=BY2
SWAY2=Y2
SURGE2=X2

NOSORT
YAWD1=DEGRAD(0,0,YAW1)
YAWDP1=DEGRAD(0,1,YAW1)
YAWD2=DEGRAD(0,0,YAW2)
YAWDP2=DEGRAD(0,1,YAW2)
YAWDPD=YAWDP1-YAWDP2
RUDDER RESPONSE INPUT
CALL RBMEAS(N,YAW1,X1,Y1,YAW2,X2,Y2,RD,R1,B1,BB1,R2,B2,BB2)
CALL HDGRAS(N,IS,R1,B1,BB1,R2,B2,BB2,RSENS,YAW2,PSIDFD,PSIADD,...
PSIDED,WT,DA,AID,BID,B2D,WTSENS,DD,RD)
BDOT2D=DEGRAD(0,1,BDOT2)
BDOTFB=VFBG*BDOT2D
DDUMB=YAWD2-PSIDED+BDOTFB
IF(DDUMB.GT.180.0) DDUMB=DDUMB-360.0
IF(DDUMB.LT.-180.0) DDUMB=360.0+DDUMB
DLTS=LIMIT(-30.0,30.0,DDUMB*RGD)
DLTE=DLTS-D2D
DLTBE=LIMIT(-DLTEM,DLTEM,DLTE)
D2D=INTGRL(D2DIC,KG*DLTBE*LUC)
D2=DEGRAD(1,1,D2D)

SORT
DISTE=ABS(DD-ADY)
OBJ=INTGRL(0.0,DISTE)
DISTES=ABS(ADX)
OBS=INTGRL(0.0,DISTES/25.0)

DYNAMIC REGION ACTUAL SEPARATION
DX=X2-X1
DY=Y2-Y1
CALL TRANS(YAW1,DX,DY,ADX,ADY)
EXTERNAL FORCES ACTING BETWEEN SHIPS
CALL SLOPES(ADX,ADY,YY1,YY2,YN1,YN2)
IF((ABS(ADY).LT.0.04744).AND.(ABS(ADX).LT.1.0)) WRITE(6,100)
FORMAT(' *****SEPARATION LESS THAN 25 FEET - COLLISION*****')
ACTUAL TIME CONVERSION (SEC)
ATIME=LUC*TIME
AA1=(BB1+BB2)/2.0
100
*
```

```

CALL SWTCHF(DD,DA,AAL,IS,RSENS,WTSENS,RGN,VFBG,BDOT2D,XOFS)
IF (ATIME.GT.450.0) XOFS=XOFS0

SAMPLE  FINTIM=30.,DELT=0.04,DELS=0.04
CONTRL  0.20,ATIME,YAWDI,DID,DLTSL,CDOT1,OBJ,YAWD2,D2D,DLTS,CDOT2,...
PRINT   OBJS,YAWDPD,ADY,ADX,SPDDDES,EMDD,WEF,WY,WN,WX,RSENS,WTSENS,...
PRPLOT  RGN,VFBG,SW

ONLY    CALL DRWG(1,1,ATIME,CDOT2)
CALL DRWG(1,2,ATIME,SPDDDES)
CALL DRWG(2,1,ATIME,ADX)

TERMINAL
IF (IS.EQ.1) WRITE(6,101)
101  FORMAT(' THIS RUN IS FOR A PORT SIDE TO APPROACH')
102  IF (IS.EQ.0) WRITE(6,102)
    FORMAT(' THIS RUN IS FOR A STBD SIDE TO APPROACH')
CALL ENDRW(NPLOT)
CALL CONTIN
FINTIM=45.0

END
STOP
FORTRAN
INSERT  SUBROUTINE RBMEAS FROM APPENDIX A HERE
INSERT  SUBROUTINE HDGRAS FROM APPENDIX A HERE
INSERT  FUNCTION DEGRAD FROM APPENDIX A HERE
INSERT  SUBROUTINE TRANS FROM APPENDIX A HERE
INSERT  SUBROUTINE SWTCHF FROM APPENDIX A HERE
INSERT  FUNCTION SWCL FROM APPENDIX A HERE
INSERT  FUNCTION SPDOFC FROM APPENDIX A HERE
INSERT  FUNCTION SPINIT FROM APPENDIX A HERE
INSERT  SUBROUTINE SLOPES FROM APPENDIX A HERE
//PLOT.SYSIN DD *

INSERT TWO /* CARDS HERE

```

4  
4  
4  
4

7.0 5.0  
7.0 5.0  
7.0 5.0  
7.0 5.0

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